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Electrification: the Entrenchment of a Phenomenon

How Infrastructure Emerges

Master's thesis in Industrial Ecology

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Göteborg, Sweden 2015

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Abstract

Transition studies often do not properly address complexity issues when analyzing technological change. Using the anthropological and biological concept of scaffolding and generative entrenchment, this thesis aims to address this shortcoming by introducing a novel perspective with a more adequate account of intra- and inter-systemic dependencies and dynamics, history, and causality of development. Ideas on the processes by which technology become "infrastructure", the increase and broadening of functionality that technology tends to undergo over time, or the concrete developmental context in which technology grows, are here merged into the multi-level perspective, which is widely-used and familiar with transition studies; also some further ideas from the studies of technological evolution are adopted and implemented.

Based on these theoretical ideas, a case-study on the electrification of the United States is performed. This case aims to exemplify the theory, starting with preceding technological developments in steam and hydropower in the early 19th century, and closing with the electrification of the US agriculture in the 1940s. Beside the insight that more complex technologies or phenomena require more complex theories to be accounted for, three overarching dynamics could be identified, which are continuing up to the present and will also shape the future of electric power systems: (i) electric power networks and their extension were largely driven by economies of scale, as a larger network is more resilient and allows for a cheaper supply of electric power; (ii) the large accessibility and availability of electric power in households and industries led and leads to huge incentives to invent and develop more and better appliances and devices that can be sold and create more usage of electricity in turn; (iii) new devices created not only strong dependencies of electric power for individuals, but, also, the spread of certain devices and appliances contributed to the emergence of new standards and norms in society.

Lastly, the theories and methods, as well as the result of the case-study and implications for the future of electric power systems are evaluated and discussed. The novel perspectives brought by the accounts of history, dependence, and technological interaction, are valuable and important for the understanding of technology and infrastructure as an evolved system with a specific history and context. From there, ideas and thoughts on the future of electric power systems are generated and discussed; especially technologies for making the electric power system more flexible on the supply and the demand side seem promising and necessary for a pesilient future of power systems.

Keywords: electrification, history of electricity, multi-level perspective, scaffolding, generative entrenchment, technological evolution.

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Malte B. Rödl, Göteborg, August 2015

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Introduction

"And these other instruments, whose functions I can't even guess?" / "Here, professor, I need to give you some background information," Captain Nemo said. "So kindly hear me out." / He fell silent for some moments, then he said: / "There's a powerful, obedient, swift, and effortless force that can be bent to any use and which reigns supreme aboard my vessel. It does everything. It lights me, it warms me, it's the soul of my mechanical equipment. This force is electricity." — Jules Verne (1870) in *Twenty Thousand Leagues Under the Sea*

Sometime in the 1930s in Ratibor (today: Racibórz), Silesia: an electrician from the local utility came to my grandma's house to equip their house with an electric power line. They had to pay him from their own money, as the landlord refused to pay for the connection; by then, most of the town's population had had access to electric power. With many children and a low income, my grandma's family could not afford so many novel or electrified devices: water, stove and oven were still heated with coal, a radio was too expensive, and other, more luxurious utilities such as a vacuum cleaner or a washing machine were out of question to buy. In fact, the only major change that the electric power connection brought was the installation of electric light. Again, most of the city, may it be domestic households or private enterprises, had had electric light, before my grandma's family could afford it; in stores and on the streets it was used for long, and many households had installed an electric power supply.

Everyone in her family was very excited about this new achievement, as it symbolized progress, and some reward for all the hard work. Ultimately electricity also brought savings in time, as there was no need to buy petroleum for the lamps anymore, and money, at least for the ongoing expenses. Electric light also provided some independence for my grandma and her siblings, as they were allowed to use it more often and more frequently than the old petroleum lights (Hecke, 2015). This was mainly because it was not as dangerous: elecrtic light produces less heat, no open fire, no explosion hazard, no dangerous fumes, and has many more advantages. In other families, in other households, in other regions of the world, similar electrification stories unfolded around this time. At first, the installation of an electric power connection was an initial expense bringing only a minor change; later however, the availability of electric power itself caused other technologies and appliances to follow.

The multi-level perspective (MLP)[1] as one of the main frameworks in transition studies faces many criticisms. Among these are the following: the theory is too broad for energy transitions where focus on detail is important (Grübler, 2012); it has arbitrary starting and end points (Genus and Coles, 2008); and Vasileiadou and Safarzyńska (2010) argue that the MLP, and many other theories in transition studies, are good at addressing transitions but do not address complexity adequately. They basically lack, for example, notions of emergence and path-dependence (Vasileiadou and Safarzyńska, 2010)—concepts associated with theory that could add important detail to our understanding. Also, the long historical past tends to be underrepresented or even ignored in transition studies or research of evolving sociotechnical systems, such as energy systems (Hirsh and Jones, 2014). in other words, it is ignored that the analyzed system is always a result of an earlier existing system: sociotechnical systems rarely, if ever, have proper beginnings. Furthermore, the multi-level perspective does not properly elaborate on the analyzed system in its specific context, because it does not account explicitly onto intertechnological dependencies.

This leads us to the first and major goal of this thesis: complexity topics such as path-dependence and emergence will be introduced into transition and technology studies while the analyzed system will be embedded into a greater societal context. This will be done by applying the concepts of scaffolding and generative entrenchment as introduced by Wimsatt and Griesemer (2007) into cultural anthropology (see subsection 2.1.1).

The resulting ideas will be evaluated and tested using a case-study: electrification. As seen and described above, while my grandma's personal electrification is unique and her genuinely own experience, it is possible to generalize experiences or happenings. Maybe for the specific narratives, this is only possible within a city, a region or a whole country, but the processes identified may be comparable or similar all over the globe. There is a great amount of literature on the history of energy, energy technology[2] or energy transitions[3]; also work focusing specifically on electrification exist[4], but none of them treats the electrification within transition studies, accounting for a specific context. Explicit elaboration on the internal societal dynamics is missing as much as the systemic relations and interdependences of the developments, or descriptions of the co-evolution of society and technology.

The novel perspective applied here would be helpful in understanding the current status of the electric power system as a result of specific historical developments

[1]The MLP is further explained in subsection 2.1.2. For now, it is only important to know its limitations.

[2]For example, Smil (1994) wrote on general energy pathways, Dunsheath (1962) and Bowers (1982) on the history of electrical engineering and electric power, and Hunter (1979) and Hunter (1985) on water and steam power in the pre-electrical era.

[3]For example, Smil (2010) wrote on energy transitions in general including some case-studies, Fouquet (2008) and Fouquet (2010) address the economic context of especially very distant energy transitions, Solomon and Krishna (2011) explores sustainability issues within energy transitions. Verbong and Geels (2007) and Verbong et al. (2008) even use the multi-level perspective to understand transition pathways.

[4]For example, Hughes (1983) explores the social dynamics and background of the electrification, though remains largely at governance and administration; Nye (1990), on the other hand, retells very well a vast amount of stories related to the electrification of the United States, but does not analyze his findings in a way related to this study.

rather than as a given system with certain characteristics and boundaries. Hence, theory and case-study play together to create an appropriate view of the electric power system as an emerged structure, shaped, influenced, and recreated by current and future developments. However, this thesis only deals with electrification processes in industrialized countries, where the it emerged endogenously from within the economy and was not superimposed by external developments or ideas, as in developing or newly developed countries where entirely different structures and social dynamics can be observed (see Murphy, 2001).
To conclude, this study aims to address the following issues:

(i) Complexity topics such as path-dependence and emergence are introduced into transition and technology studies by applying the concept of scaffolding and entrenchment as introduced by Wimsatt and Griesemer (2007), where the analyzed systems are not only embedded into a societal and technological context, but also embed other technologies and practices. The aim herewith is to account for a technology in its context, trying to understand why and how it *becomes* relevant, but also why and how it *remains* relevant, or fails.

(ii) Electrification is analyzed as a sociotechnical transition, focusing on the external structure that allowed the electrification and that led to the first electric power systems, as well as the internal dynamics, that occurred within society as a result to the new technological allowances. The process of the case-study itself is used to apply the ideas and framework and to evaluate its usefulness for future research.

(iii) The long-term history and the developments preceding the start of the electrification are elaborated and looked upon, to put the novel achievements and later developments into a societal and technological context.

Apart from the introduction, this thesis has four further chapters. At first, Chapter 2 elaborates on the theoretical background and underlying theories (section 2.1) and the resulting ideas and framework for the subsequent analysis. With Chapter 3 follows the largest part and case-study for this thesis. After some physical backgrounds on electricity and electric technology (section 3.1), this chapter elaborates upon the preceding developments of the electrification (section 3.2), as well as the electrification itself (section 3.3). The chapter closes with a very brief account on the electric power system after the electrification, including some perspectives on current and future developments (section 3.4). In, Chapter 4, a discussion follows on the findings of the case study (section 4.1) and the methods (section 4.2), as well as a discussion on what the findings may contribute to the future of electric power systems in specific, and transition studies in this sector in general (section 4.3). The thesis closes with some conclusions on methods, and results, as well as with future research ideas (Chapter 5).

2

Theoretical Considerations

In becoming deeply entrenched, elements become more like infrastructure as they become more polyfunctional: as infrastructural elements are coopted for more functions because they are there, they become more deeply entrenched, and in consequence, more strongly conserved, causing a mutual positive feedback of amplifying stability relations. Thus one can build infrastructure to facilitate the amplification of structures and processes utilizing them, but one can also simply use what is there to such an extent that it becomes *infrastructural.* — Wimsatt and Griesemer (2007, p.280)

As mentioned in the introduction, this thesis is trying to address topics from complexity research such as emergence and path-dependence within the research on energy systems. The electric power system is not only a complicated system, but its historical development and pathways are rather of complex nature involving many different actors and institutions. Therefore, tcked one, requiring narrative theory (see Andersson et al., 2014). The framework developed here utilizes narrative theory: it seeks to explain the process of the electrification by integrating societal and economic complexity and complicatedness, while storylines of societal and technical developments are used to make sense of the underlying processes.

This chapter covers a short elaboration on the concepts underlying and inspiring the theoretical ideas used in this thesis. Building up on this, some further concepts for the following case-study are envisioned and proposed as one potential perspective to analyze complex systems in transitions.

2.1 Theory

There are three fundamental theories or inspirations for this thesis: most important are the concepts of scaffolding and generative entrenchment, originating in biological evolution and introduced into cultural development by Wimsatt and Griesemer (2007); further inspiration came from the transition studies in form of the *multi-level perspective* (MLP) by Geels (2002), as well as from technology studies via Arthur (2009).

2.1.1 Generative Entrenchment and Scaffolding

Generative Entrenchment (GE) is a concept deriving from evolutionary biology to explain how new features necessitate and build up on each other. Wimsatt (1999) and Wimsatt and Griesemer (2007) adapt this concept to explain cultural development. This adaptation serves as an inspiration to this thesis where it is applied to electric power systems and electrification.

The basic idea of the concept is that any new development, such as a new skill, a technical achievement, or even a societal agreement, builds up on some other, already existing developments. This is process is called scaffolding: the use of artifacts or infrastructure[5] to achieve a developmental function. That function is the "facilitating acquisition of a capacity that the target or an actor in the collective did not have before (or would not otherwise)" (Wimsatt and Griesemer, 2007, p.281), where maintenance is explicitly excluded. While an artifact is some rather short-term, artificial thing in the society, it can become an infrastructure if it is used constantly and over a long period of time in many scaffolding interactions. This may be either planned as such—for example a highway or a modern electricity grid which are intended to be used by many processes and interactions—or may achieve a role equivalent to infrastructure through a change in the environment or the scaffolded developments. Written language, for example, was not erected as a cultural infrastructure but developed in a long process, and is still changing (Wimsatt and Griesemer, 2007).

Any infrastructure or infrastructure-like artifact is used for many developmental purposes, and hence over time, society becomes dependent upon this object; the object becomes entrenched. This process may be a self-maintaining, positive feedback loop—i.e. the existence leads to usage, the usage leads to dependence, and the dependence leads to conservation or reinforced existence (see also Figure 2.1)—which Wimsatt and Griesemer (2007) call *generative entrenchment*:

> "In becoming deeply entrenched, elements become more like infrastructure as they become more polyfunctional: as infrastructural elements are co-opted for more functions because they are there, they become more deeply entrenched, and in consequence, more strongly conserved, causing a mutual positive feedback of amplifying stability relations. Thus one can build infrastructure to facilitate the amplification of structures and processes utilizing them, but one can also simply use what is there to such an extent that it *becomes* infrastructural." (Wimsatt and Griesemer, 2007, p.280, emphasis in the original)

The entrenched object defines at least some of the boundary conditions for a properly-functioning system, for the normal operation of society. Thus, the magnitude of generative entrenchment of an object can be approximated by the "reach of the damage or the spread of the change" (Wimsatt and Griesemer, 2007, p.284) once this object is removed or damaged. "Since the probability that a change will be damaging goes up rapidly with the size of the change and number of things affected, the generative entrenchment of an item is a good predictor of its evolutionary conservatism"

[5]In fact, Wimsatt and Griesemer (2007) include also developmental agents—other actors that facilitate the acquisition of a function—into their definition. However, this notion is not of interest in the current study and therefore omitted.

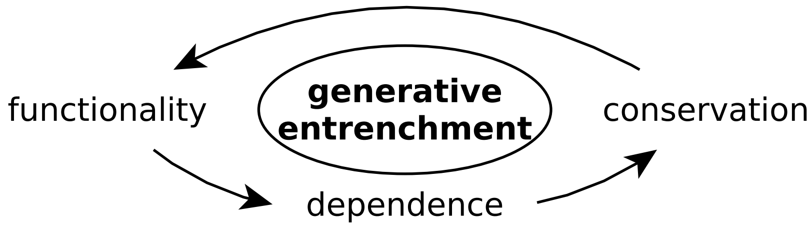

Figure 2.1: Generative entrenchment. A positive feedback from increasing functionality, entrenchment, and conservation.

(Wimsatt and Griesemer, 2007, p.284).
An example should clarify the concepts a little further: so given you build a new house and you need to install piping for fresh- and wastewater, there are many things you need. First of all, you need a plumber, respective tools and a network or interfaces to connect to, as well as raw materials, tools and infrastructure to manufacture the piping and to bring everything to your new house, which uses transport infrastructure, probably the help of gasoline, coal, electricity, and many more things. All of those components make the concrete application of this technology—piping in our example—in these circumstances possible and therefore allow your house—and therefore you yourself as a resident—to gain a new development state with incorporated fresh- and wastewater management. Furthermore, they scaffold the deployment of the piping; while some elements, like the tools, are replaceable and ubiquitous artifacts, others are entrenched infrastructures or infrastructure-like systems, such as the water infrastructure or the transport infrastructure; also, there are development agents that facilitate the construction. The more developmental actions these underlying infrastructures or tools scaffold, the more entrenched they become; in case this spectrum of developmental actions is self-reinforcing as a result of increasing functionality (see Figure 2.1) because an infrastructure allows many different and continuous ways to use it; this is Wimsatt and Griesemer (2007) call generative entrenchment. This can be even the case for the newly installed piping infrastructure, if you decide to use your water access not only to shower, but also to do agriculture, power a small engine from the water pressure, and wash clothes and dishes with it.
In later sections of this chapter, the ideas of generative entrenchment and scaffolding are taken up again, and are adapted and extended to the needs of this study.

2.1.2 Multi-Level Perspective

The *multi-level perspective* (MLP) (Geels, 2002, 2004, 2005, 2010; Geels and Schot, 2007) is a framework to look at sociotechnical transitions; there transitions may be seen as often successful attempts to technological change. The framework is designed to analyze transitions in so called sociotechnical systems which include not only production and diffusion, but also use of technology (Geels, 2004). Generally, it describes on how interactions within sociotechnical systems and regimes take place,

how they co-evolve with each other and in which ways this shapes and influences sociotechnical transitions. Though not explicitly mentioned during the case-study, the MLP constructs the main framework on the interaction and development of the sociotechnical systems analyzed in this thesis; however, not all aspects of this framework will be treated as equally important and might be ignored here.
The main component is the multi-layered nature of the system (see Figure 2.2): the *landscape* shapes the general long-term setup of the sociotechnical system, such as culture, political system and so forth (Geels, 2004). Within this landscape, *sociotechnical regimes* exist and interact, each regime with its own rules and practices inherent into the regime. An important characteristic of a sociotechnical regime is that it brings together all the actors and interactions involved, and includes all the common and shared practices—especially for economic factors, technology, science, politics and the sociocultural environment—evolving around this sociotechnical object, which Geels (2004) names technological regimes or sub-regimes. These regimes co-evolve in a way that changes in one sub-regime are followed by changes in another and vice-versa. Lastly, a *niche* is part of such a sociotechnical regime; initially unchallenged and protected from major competition, it may or may not undergo a successful transition into the sociotechnical regime, potentially replacing some old technologies (Geels, 2004).

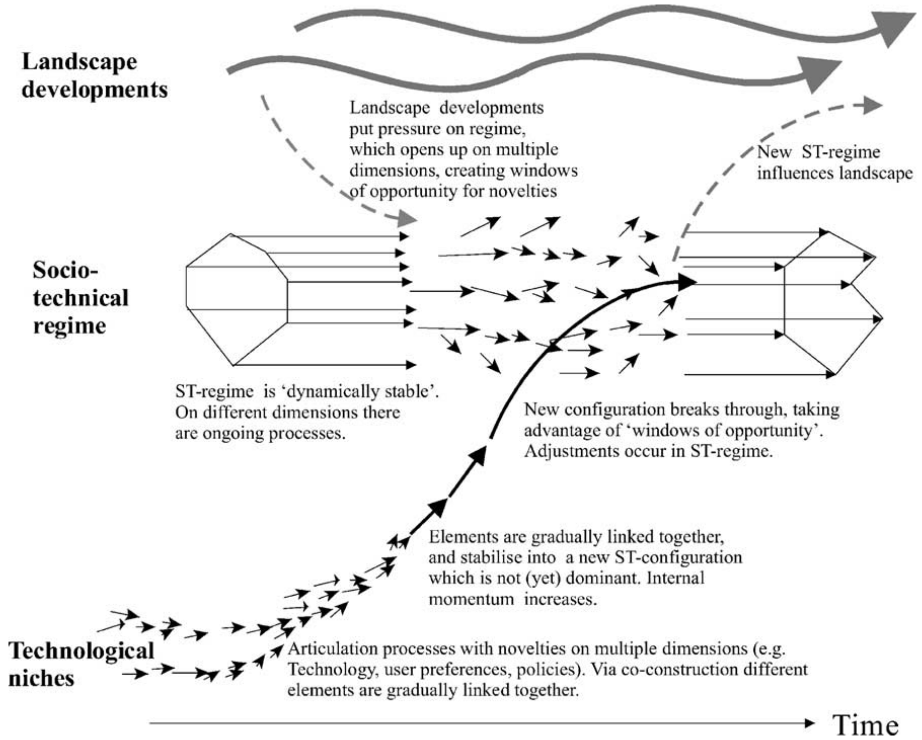

Figure 2.2: An illustration of the basic framework of the multi-level perspective (Geels, 2004, p.915).

When comparing the levels of the MLP with the idea of generative entrenchment, sociotechnical regimes may be analyzed as scaffolding or scaffolded elements. In this case, the degree of entrenchment defines the position of the regime in the landscape-regime-niche spectrum: the landscape, or the core regimes, are formed from mostly older, deeply entrenched regimes that are extremely difficult and reluctant to change. On the other hand, niches, or peripheral regimes, are small, new and seldom scaffolding regimes that due to their small size and low amount of interactions hardly face any pressure from markets, competitors and others, while they still contribute to entrench other systems.

In between all these regimes, there are many interactions happening. Current changes on the landscape level can influence a regime or may put pressure on it, opening up so called *windows of opportunity* for niche technologies (Geels, 2002). In turn, a predominant idea in the regime can influence the landscape level substantially. The same accounts for the niche, which, once it grows, challenges the regime as well as the landscape and the inherent practices, but is also pressured by landscape and regime and their respective ideas to which the niche has to adapt to be successful (Geels, 2002).

Going back to the example of the piping installation, the MLP cannot contribute so much here, since it deals with technological transitions. However, the example serves well to explain some features: usually, the more entrenched an infrastructure is, the more it is part of the landscape rather than a regime. So the existing water network, including pumps and treatment plants, are probably part of the landscape-level of the structure, while, in contrast, the plumber, the pipes, the contract with the local utility and many more things are part of the sociotechnical regime. In case the established technology proves to be inferior compared to another technology or towards new environmental conditions, new windows of opportunity are opening up for this new technology—for example, on-site cleaning of water could be more efficient or more resilient towards environmental hazards than a network access. In this case, a niche for the new technological solution is established, and forces the existing regime or even landscape to adjust and to make up for the drawbacks that are visible in the new context. Ultimately, the new technology might or might not be able to challenge the regime, which is reflected in its entrenchment.

2.1.3 Technological Evolution

The Nature of Technology (Arthur, 2009) is a widely acknowledged work by economist Brian Arthur on technology and its evolution. For this thesis, some of his ideas are helpful to get a better understanding of technology, as well as some further perspectives on technological development in a timeframe longer than merely a single transition[6]. In contrast to the ideas of scaffolding and entrenchment (see Wimsatt and Griesemer, 2007), which is a theory on concrete external support structures, the contribution of this author is focusing on abstract internal dynamics, disregarding time and space.

His definition of technology includes any *means to purpose*, so that any object, artifact, or even meme with a functionality can be called a technology. Besides the classical understanding of technology, this can include practices, behaviours, or even

[6]As already mentioned in the introduction, Genus and Coles (2008) claim, that the arbitrary and subjective definition of starting and endpoints for the analysis of transitions with the multi-level perspective can lead to a variety of different outcomes. Furthermore, does the multi-level perspective only focus on a single transition rather than a a series of transitions within a field, or a multitude of different regimes for a single technology.

elements with coordinative function such as money or laws. Technologies are formed by three different processes, that can make up the whole variety of technology: (i) *combination* of different technologies; (ii) *recursiveness* of technologies and sub-technologies; (iii) *exploitation* of an effect or phenomenon on the basic level.

Here it is important to understand the concept of a phenomenon as opposed to the concept of a technology, as this differentiation is quite central to this work: while a technology is an artifact in the technosphere following the rules above and having this specific function, a phenomenon is simply a concept, idea, or relationship that is being harnessed to fulfill this function. For example, that burning gas produces heat can be a concept, while a gas burner, gas stove, gas oven, and many other devices utilize this phenomenon, and most likely many more.

A specific cluster of technologies is called a *domain*, and it evolves around specific phenomena, technologies that share a common purpose or have similar attributes; it is a "collection of practices and knowledge, its rules of combinations, and its associated way of thinking." (Arthur, 2009, p.70), which is basically a technical description of sociotechnical regimes by Geels (2002, p.1260) as "the semi-coherent set of rules carried by different social groups". In this context, Arthur (2009) also describes how new domains emerge from significant innovations and how they are shaped by the parental domain; he especially draws attention to a point that a technology will be most successful if it explores new applications (so that it has some kind internal generativity) and if it forms its own domain.

Arthur (2009) also describes further interesting dynamics within innovation processes that are termed the *natural cycle of innovation*: on the basis of such a cycle stands the discovery of a new principle which is followed by initial exploitation where the technology spreads, diversifies, differentiates and eventually forms out its own domain. After a while, the limits of the respective technology—for example performance, functionality, adaptability, safety—are reached and new technologies or sub-technologies need to replace those where the limitation occured; this replacement is able to improve the technology and push its respective boundaries further. The internal replacement of components almost necessarily leads to an increasing complicatedness of the technology itself which Arthur (2009) calls *structural deepening*. When a technology subsequently reaches maturity at a high performance, there might be the case when the limitations cannot be overcome anymore. In this case a new principle for fulfilling this purpose is needed, but the old technology often is locked in; this *lock-in* might be not only because of reasons of performance but of various reasons, as described in the following section. Before a new technology is able to supersede the old technology, the incumbent performs an *adaptive stretch*, that is to cover new fields despite its potential inferiority, simply because it became a custom to work with this technology.

Again, the example of the piping network will be utilized to clarify the ideas: the whole piping network, the single pipe, and even the tools are a means to purpose, they fulfill an important function, which in its entirety can be called the domain of water management. A single of these technologies, for example a single pipe, is a combination of different sub-technologies: a round tube, and a connecting interface, which in this case are the same object, but fulfill different functional purposes. Each of these can consist of different sub-technologies again, and ultimately a sub-technology relies on a specific phenomenon or effect. For the pipe this might be the material that is not soaking wet, safe against many chemicals, flexible and formable, and the round shape that provides the best through-flow per material unit and the highest strength against pressures. With the previous example of on-site water cleaning, also the natural cycle of technology might be explained, though this theory does not look at a replacement process but rather the cycle of a single technology.

The examples of the piping networks illustrate nicely, how the different theories work and interact. While generative entrenchent and scaffolding discuss the surroundings in which technology works in, and the possibilities that it brings, the MLP can explain how this technology came into place or can be replaced. Lastly, this theory can contribute to the internal structure of technology, how it is set up, and how novelty and change come into place from a perspective of technological evolution.

2.2 Barriers to Change: Lock-In

All those three authors mentioned include the notion of a development state, that can prevent change from happening. Maybe the most well-known terminology for this state is "*lock-in*", also often mentioned in combination with the concept of path dependence. This state is central to transition studies, as it is often the main limitation for the success or failure of a transition. There are many different circumstances in which this state is relevant, for example, in business and economics (Arthur, 1994), technology and innovation (Arthur, 2009; Foxon, 2014), sociotechnical systems (Geels, 2004), interaction games (i.e. game theory) involving learning effects (Fudenberg and Levine, 1998), artifact-dependencies (Wimsatt and Griesemer, 2007), culture and habits (Collins, 2014), or even in biology (Laubichler and Maienschein, 2007).

Maybe most well-known of these concepts is the economic notion of increasing returns by Arthur (1994); he distinguishes four different classes of these which may all create a lock-in state: (i) *scale economies*, the decline of unit costs with an increase of output; (ii) *learning effects*, which reduce unit costs over time due to knowledge accumulation, product specialization or experience; (iii) *adaptive expectations* as confidence tends to increase and uncertainty to decrease with increasing maturity of the technology; (iv) *network or coordination effects* which occur when advantages increase when many agents adopt the same technology, such as communication. He also refers to the terms rigidity and inflexibility as being preferable to lock-in (Arthur, 1994).

With respect to technology, lock-ins can not only occur in the above mentioned categories of increasing returns, but can also be related to the infrastructure. As infrastructures are commonly developed for existing technologies, attributes of future technologies have to conform with these features, because otherwise they cannot build on existing structures; in this case, they would have to create their own or adapted infrastructure. In consequence to this unfavourable conditions, existing infrastructure and its features are highly locked-in (Foxon, 2014). This may especially occur in sectors with high market entrance cost because of the comparatively high infrastructure investments and a smaller market demand [7].

Geels (2004) identifies three different but interrelated ideas of lock-in in sociotechnical systems, which all provide stability within the current regime and make it more difficult to induce change: (i) existing formal and emerged rules; (ii) interdependent networks and dependencies of actors and organizations; (iii) physicality of large artifacts or infrastructure.

A novel perspective on these lock-in phenomena for technical systems is Wimsatt and Griesemer's (2007) concept of generative entrenchment which, in fact, only makes the already mentioned more explicit when embedding it into a larger picture. While all the mentioned ideas are largely existing within a technological regime, the concept of entrenchment introduces the sociotechnical importance of an artifact or infrastructure which is displayed by the multitude of scaffolding interactions it provides. Generally, the degree of entrenchment is defined by the amount of necessary change or induced damage upon removal or change of the entrenched element. While a peripheral technology has none or only a few interactions to serve, a core technology—i.e. one that serves more different scaffolding interactions—can only be changed with a much bigger impact (see Figure 2.6).

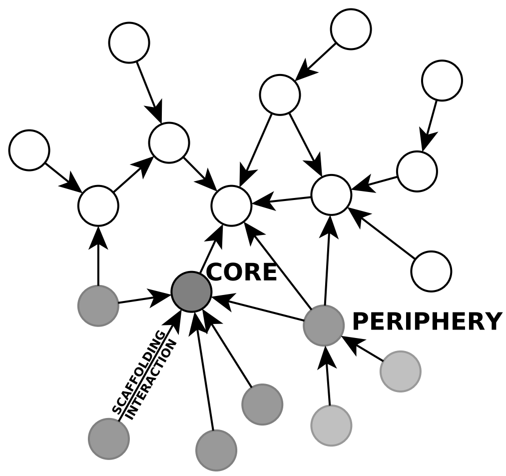

Figure 2.3: The generative entrenchment of technologies in different sections in the core-periphery-spectrum. The more scaffolding interactions are supported, the higher the importance and thus the impacts upon removal of this element; in consequence, a hierarchy of dependencies is created by the multitude of scaffolding interactions.

[7] This market situation is called *natural monopoly*. Research on this field actually started in the early 20th century focusing on electrical utilities and "[one] private producer of electricity in particular helped subsidize the research on which the theory was based" (Dorman, 2014, p.291).

2.3 Scaffolding for Niche Technologies

The presented ideas on the evolution of technology largely leave out the final application and the developmental context of technology, which is necessary to look at within technological transitions; this is where the concept of scaffolding from Wimsatt and Griesemer (2007) can be important for understanding technical evolution and change in a specific sociotechnical context.

New technologies can come into existence by two fundamentally different mechanisms: a technology-push resulting from, for example, innovation cascades after the discovery of a new phenomenon or the development of a new technology (see Arthur, 2009), or by technology-pull related to an open window of opportunity and focused research and development actions towards this (see Geels, 2002).

Once a new technology comes into place, it opens up a new market niche, a peripheral regime completely unentrenched because it has not been used anywhere yet. Upon development towards becoming a viable competitor technology in the market, there are various different scaffolds[8] facilitating this process and lifting the technology towards more entrenchment, i.e. more relevant application for society as any scaffolding interaction serves a developmental purpose. Especially in a historical, weakly globalized and not completely industrialized context, a few interesting scaffolds can be observed because of the smaller size and separateness of potential markets and because of weaker international and especially transatlantic communication channels. These partly outdated—i.e. nowadays less relevant—scaffolds can range from knowledge transfer via journals and/or books, prices for innovations, local or regional business culture, to institutionalization, attitude towards quality assurance, and even the specific skills and experiences of the individual craftsman.

Another noteworthy point has to be made on the interactions and mutual scaffolding of technologies: not only is it possible that two complementing, or even competing, technologies mutually scaffold each other's development, but also is it possible that a single technology scaffolds a series of competing technologies, depending on the development stage of the scaffold and the technologies in question. Both can be observed in the shared history of water power and steam power in the 19th century, which is elaborated later in section 3.2.

Especially in a historical context, as mentioned above, it is important to embed the transition in question into the specific and local developmental circumstances, as these are the scaffolds of development, rather than the general technological perspective or market. This context-aware analysis compromises: (i) the *environmental context* which includes the local terrain and natural boundary conditions that shaped, influences or hinders, for example, previous application or current adoption; (ii) the *technical context*, as the whole system of the local application, for example the whole supply chain and factory building and the specific process necessities; (iii) the *functional context* that relates to previous technologies, including the necessitating physical or practical legacy features, restrictions, management, maintenance, or even workflows; (iv) the *social context* that includes personal networks

[8] Often the term "driver" is used in business-related studies on technological transitions. In contrast to this unclear terminology, the term scaffold clearly defines a direct external assistance towards reaching a new developmental function.

and knowledge of the local decision-makers, their ideas, preconceptions, character, personality, and approach towards business or change. Although all of these notions can be found in parts in the sociotechnical regimes as described in Geels (2004) and applied in the multi-level perspective, they are rather meant and used for general market conditions rather than for a specific application. Of course these notions may also be generalized towards system-wide boundary conditions, but then the concrete complexity of any case in any specific context cannot be understood to the fullest.
Once the initial niche is set and tries to reach maturity, it has to compete against the pressure from more entrenched regimes which want to maintain their technological position. For this, the dominant and entrenched regime has to be challenged; this means, it has to be disentrenched. There are many different interactions that can lead to this state, but the basic idea of all of them is to either scaffold the new technology in a secure context, or to create a parallel structure to challenge the singular entrenchment of the established system. Wimsatt and Griesemer (2007, pp.295-296) mention five mechanisms which that can be encountered in the case-study frequently: (i) riskless trials of new technology due to security and redundancy given by the predominant regime; (ii) functional decomposition of the entenched object in a sense of Simon (1962), so that different functions of a technology can be fulfilled by different devices; (iii) natural redundancies provided by early and late adopters who can serve as change agents or backup opportunities; (iv) increasing transparency by management of scaffolded structures, such as “black-boxing” or “backwards compatibility” (Wimsatt and Griesemer, 2007, p.296); and (v) reducing singular dependencies and introducing redundancy or hybrid systems with parallel structures. Furthermore, two more mechanisms can be added to the list, which appeared important in specific cases in the later following case-study: (vi) low technological opportunity cost by redomaining existing but outdated artifacts or infrastructure; (vii) protected environments such as special applications that cannot sufficiently be filled by the predominant regime.

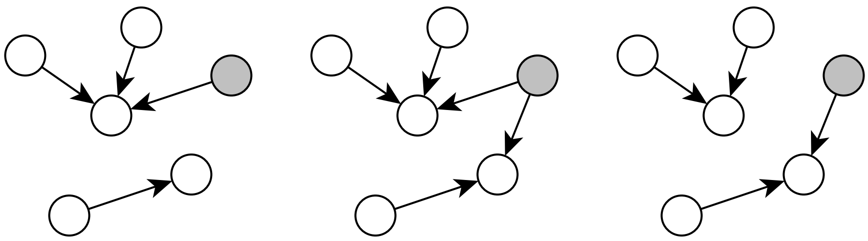

Figure 2.4: Rescaffolding of an element. The highlighted element changes its dependence from one to another element via a state of redundancy.

The consequence of any of these processes is that the scaffolding environment is being restructured with respect to a single scaffolding interaction or a group of scaffolding interactions: at first, an element is scaffolded only by the conventional technology, then later by both, and ultimately—although co-existence is possible, especially when considering inequalities in context and boundary conditions—by the

novel technology (see also Figure 2.4). However, as a contrast to the conventional idea of transitions, this idea of rescaffolding is not necessarily the replacement of a technology. Instead, a certain application replaced another application in a very specific context or group of contexts ; however, as other elements might continue relying on the conventional element, this does not necessitate a technological transition, as other contexts or application might still require the partially replaced technology. In section 4.1, the importance of rescaffolding as compared to novel applications for a technology is further elaborated.
As a consequence of novel scaffolding interactions, a niche can increase in its societal importance as it is used for more and more scaffolding interactions itself. Ultimately, upon success, the new element can reach some kind of viability and maturity in the system, while simultaneously becoming entrenched slightly. How this happens, and how a technology might become infrastructural will be discussed in the next section.

2.4 Becoming Infrastructural: Generative Entrenchment towards the Core

While the early phases of technology transitions are largely about what kind of system a technology builds upon (so about what scaffolds the technology), the more mature a technology gets, the more it becomes important what is being scaffolded by this technology. In a way, the technology becomes an active and more generative facilitator within the system, rather than just using other infrastructures for singular purposes.
During this process, the developing sociotechnical regime moves towards the core and becomes more mature by emerging practices, rules and networks around the technologies, but also it becomes more challenged by other regimes or emerging niches (see Geels, 2002). As a consequence of the increasing importance, the technology becomes standardized and thus inflexible in its technical nature, while at the same time, through its increasingly universal availability, it becomes more polyfunctional and is used by more and more other technologies and regimes as a scaffold; simultaneously, organizational practices and the whole sociotechnical regime around the technology will co-evolve towards a standardization as a more and more deeply entrenched and thus economic system develops (DiMaggio and Powell, 1983; Geels, 2004). This increase in functionality coupled with higher quality and better availability through conservation, standardization and maintenance is exactly the powerful positive feedback loop of *generative entrenchment* which Wimsatt and Griesemer (2007) describe.
The more entrenched an element becomes, and, therefore, the more it develops towards the landscape level—which certainly not every technology manages—, the more it will behave like infrastructure: it will involve permanent structures in the environment, it will involve universal access, it will involve political as well as economic conservation because of its significant importance for many different processes and developmental actions.
For analyzing the process of entrenchment further, different subsystems (see Simon, 1962) may be identified and treated individually with respect to generative entrench-

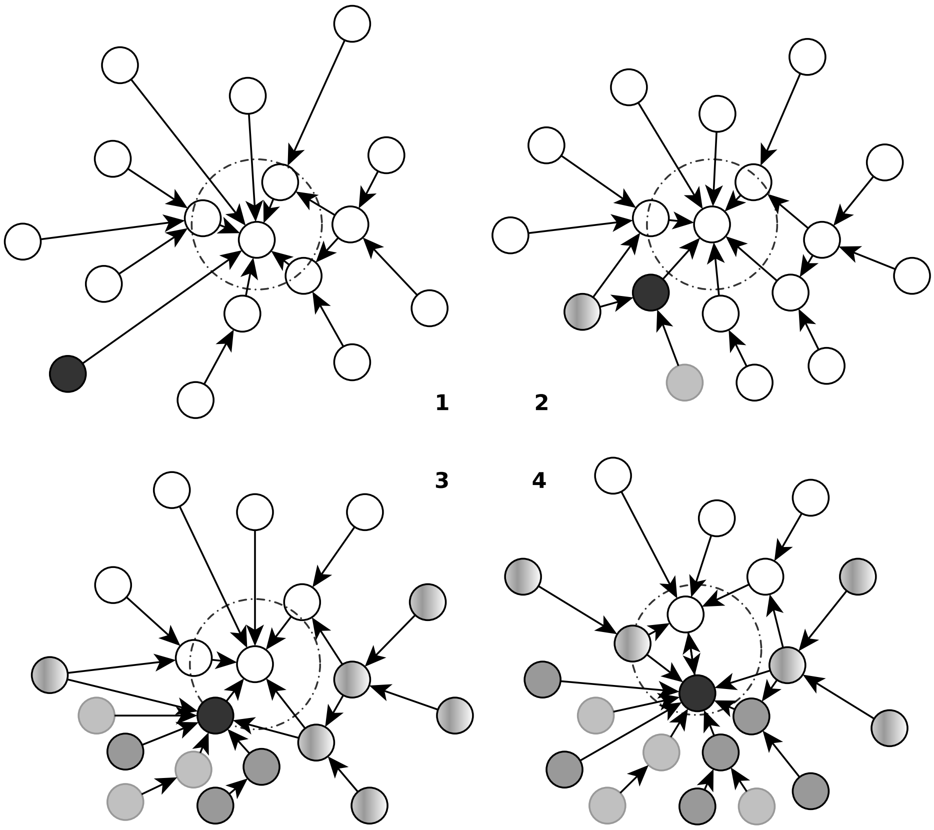

Figure 2.5: The entrenchment of an element towards the core. The element in question (dark grey) develops towards the core by serving an increasing amount of scaffolding interactions of novel (light grey) or old applications (medium grey), and of partial dependence in parallel technological dependencies (white-grey).

ment, as each of these subsystems might have its own reasons for a certain development. However, the overarching dynamics with respect to technological learning effects and the subsequent technological change are still crucial for understanding the overall entrenchment.
Generative entrenchment, in general, can be arranged and observed in many different ways. The following two sections elaborate on the mechanisms of increasing functionality and conservation in a sociotechnical context.

2.4.1 Functionality

The increasing functionality is central to generative entrenchment, while, on the other hand, the achievement of developmental functions is central to scaffolding. Since generative entrenchment is the multitude of reoccuring scaffolding interactions with a single, stable artifact over time, it has to be found out, how increasing functionality can add developmental functions. For this it is important to realize, on the one hand, what role the scaffold plays in achieving the developmental function, and, on the other hand, what the new functionality means for the entrenchment.

To answer the first question, we can look into modern production systems as an example and may identify during which phase of the product's life cycle the scaffolding interaction occurs[9]: (i) the scaffold can be used during the manufacturing or production stages of an artifact, which includes raw material harvesting as well as pre-retail activities; in this case, the developmental function can exist in temporal and spatial independence of the manufacturing process; (ii) the scaffold can be used to supply the applying agent with the artifact, which includes transport networks, retail, and eventually also communication networks for informing agents about the inherent functionalities, such as done via advertising; (iii) the scaffold can occur during the use-phase of a product, so that the developmental function can only be achieved when the product is necessitating the scaffold, such as electric energy. Following the complete life-cycle, also disposal and recycling needed to be included, but they are omitted in this thesis. Depending on the type of artifact, whether it is a long-lived artifact or consumption good, any of these phases can become critical within the scaffolding chain. The absence of electricity, for example, may have effects on all three stages: when electric power is used for the manufacturing process; when it is used for managing or even facilitating the supply, such as the electric pumps in fuel stations or electric traffic lights, but also the installation and set up for more stationary goods; or when electricity is necessary to use an artifact directly when electricity is required by the artifact, or indirectly when electricity is required to create an appropriate context to use this artifact, for example, electric light for reading a book during nighttime.

The second question, about the meaning of functionality for entrenchment, is a little bit more difficult to answer; generally speaking, there are two fundamentally different types of new functionalities, which both combined make up the power of generativity: on the one hand, a new functionality can be added to the multitude of scaffolding interactions, so that the quality and diversity of scaffolding purposes increases. On the other hand, an existing functionality may be used to an increasing extent, such as happening in diffusion processes on a macro-level; also increasing returns (see section 2.2) or rebound effects can be seen as quantitative change. However, these notions are not always clear to distinguish, as the idea of quality and quantity differs with the perspective, whether from a technological perspective or an agent-bound perspective. While from the perspective of the technology, an innovation is adding new functionality to the scaffolding options, only adoption and usage of this new functionality is sufficiently entrenching it. On the other hand, from a perspective of the agent, only new interaction opportunities for scaffolding can be achieved when a new artifact is acquired, whereas the dependence increases with the amount of change it induces.

Obviously, at first a new functionality has to be added to an element, before it can become entrenched by an increase in usage. The functionality can either come from substantially new applications, or on the other side an existing functionality can become newly scaffolded when the previously entrenched state is resolved and for some reason, such as a functional or economic incentives, is now scaffolded by

[9] This threefold structure of manufacturing, distribution, and usage resembles the structure identified in the next chapter for electric power systems, which are separated into generation, transmission, and application.

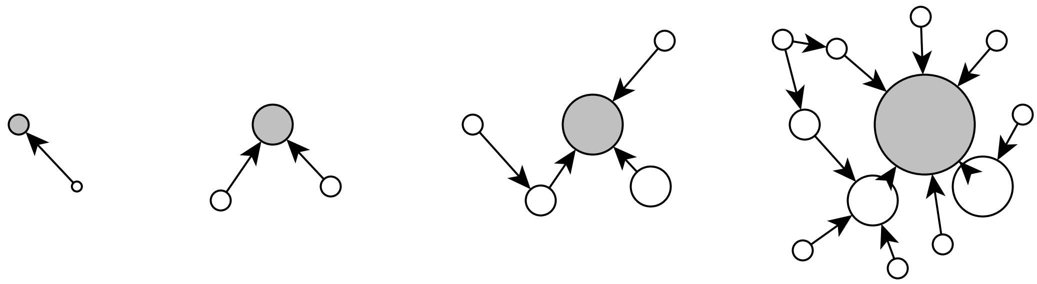

Figure 2.6: Scaffolding of an isolated technology and its increasing entrenchment on a quantitative (higher level of dependency) and qualitative (more different dependencies) basis.

another element (see Figure 2.4).
Generally speaking, while new functionality can be added only once, the usage of any functionality can be increased indefinitely, unless saturation occurs, for example, because the amount of potentially adopting people or of usable space is limited. Others seem like they have no limits, for example abstract concepts like risk minimization or network integration, as change in these respects is still continuing. Although certainly an insatiable functionality is longer lasting, this does not say anything about the effects of the functionality, as this is independent of societal or economic importance represented by the amount of scaffolding interactions.
Within the analogy of evolution, it is probable also an infinite amount of technologies exists (see also Arthur, 2009). These are all part of new functionalities which may be scaffolded and thus facilitate the entrenchment of the scaffolding technology. However, there may be certainly some more generative and some less generative technologies; a phenomenon in Arthur's (2009) sense is the most generative of all, while the most specific technology is probably also the least generative.

2.4.2 Conservation

Any increase in functionality leads to an entrenchment of the specific scaffold and in turn increases its conservation. This is what we know about conservation so far. But what leads to conservation of the entrenchment?
Looking at different stages of the life-cycle, it seems that the use-phase is the most entrenching scaffold, as manufacturing and distribution are employed only once, while the use phase involves ongoing scaffolding interactions for durable goods. When a scaffold is only used for production, it becomes much easier to replace it, since the change can be resolved at an instant, just in the moment when a new production scaffold is introduced. Theoretically, the same accounts for the distribution phase. In contrast, when a scaffold is necessary in the use-phase, such as electricity, then the amount of change required to alter this scaffold is much larger because it cannot be resolved in a singular action, as the application is usually distributed over various locations and another scaffolding technology might necessitate a different context.

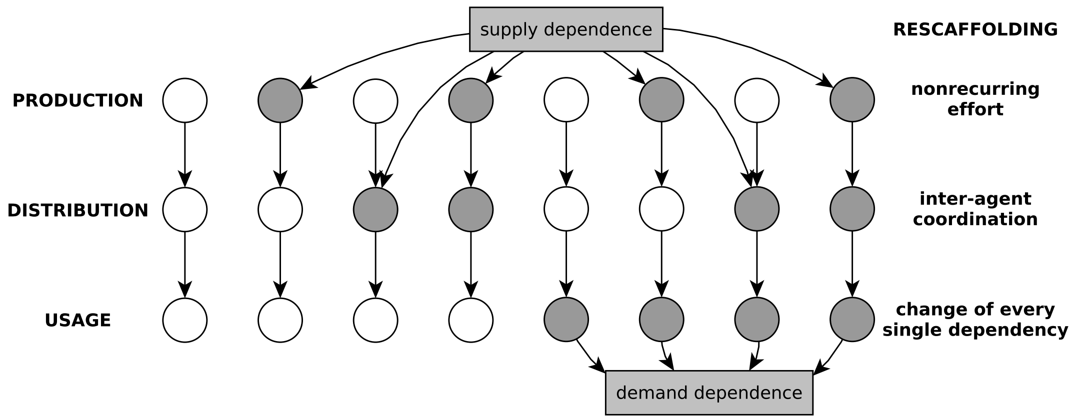

Figure 2.7: Supply-chain dependencies and rescaffolding efforts. While the production processes need a unique and nonrecurring intervention, changing the distribution requires some inter-agent communication to alter the transport system properly, and changing the usage dependency requires changing every single instance of an appliance.

In addition to that, any new function represents a new stakeholder who wants to avoid change in the scaffold, while an increase of usage increases the interest this stakeholder has in conservation. This can be motivated by many different reasons, and any generalization is difficult. Generally, a distinction into economic reasons, i.e. the scaffold makes a certain task more affordable, and systemic reasons, i.e. the scaffold became necessary to avoid chaos, seems appropriate but involves normative judgment on the necessity of developmental functions. And of course, the one might lead to the other, and vice-versa. Furthermore, it is important to notice, that a systemic conservation in a somewhat capitalistically-driven society, will imply economic reasons for conservation since decision makers will make it economically relevant if a systemic necessity is given.
These reasons for keeping a scaffold can occur in various different contexts, such as production systems, societal structure, physical or technical necessities, personal behaviour, or even because of coercive effects. However, any of these conservation mechanisms is very process-specific and any introduction of a general context seems unfeasible.

3

Electrification – a Case-Study

It bordered on the supernatural, and the Edison light, the Brush arc light, any form of artificial light, astounded people because it violated the natural order. Arc lights conformed somwhat to what lighting "ought" to be; they flickered a little, their carbon elements burned down like candles, and they were quite hot. But the Edison light was unlike all previous lights, whether candles, oil lamps, torches, fires, or gas mantles. Light by definition had always implied consumption of oxygen, smoke, flickering, heat, and danger of fire. For all of human experience, light and fire had been synonymous. — Nye (1990, p.2)

From today's perspective we take most of the energy infrastructure—electric networks, gas pipelines, power plants, district heating—for granted. Although we do not always interact directly with these structures they open up a vast field of affordances for daily life: easy and convenient ways to obtain light, food, heat, traction, communication, and many more.

It is impossible to define the most important infrastructure—they have a long history of mutual facilitation and co-evolution leading towards interdependences—but energy plays a remarkable role in all fields of society and the economy, and maybe the most important form of energy is electricity. So to demonstrate the application of the theories introduced in the last chapter, the process of electrification shall be used as a case-study: to be precise the electrification of today's industrialized societies, at the example of the United States of America, in the decades around the year 1900. The advantage of exploring an energy-related infrastructurization for this case-study, is that energy is highly connected with the complexity of society (Tainter, 2011) and thus provides a good case for exploring the interplay of technology and society.

At the bottom of the emerged electric system lie its physical properties. Its major affordances and constraints either scaffold or prohibit innovation and development, but are also ultimately responsible for the generativity of the electric system. These properties will be elaborated upon in the first section of this chapter and form the context of the subsequent analysis.

This physical context will be complemented with technological developments in the second section: it will elaborate on the advancement of science, technology, and engineering practices and thus draw a detailed pathway of a scaffolding history leading towards the electrification of major parts of human life. This account mainly focuses on the motive power systems that were used for generation of electricity later, as well as the context in which these developments occured; it will be concluded with

some explicit hints onto the scaffolding developments mentioned in the theoretical elaborations.
Having thus set the scene, the third section deals with the societal aspects of the electrification. It will cover the range of involved actors, the relations and interactions that allowed the entrenchment of the electric system, and it will elaborate on the generativity of the entrenchment process. These entrenchment processes will be analyzed by using the theoretical ideas which were described earlier.
Of course, once the electric system had become what might be called an infrastructure, there were more processes and dynamics that strengthened its role as such and that entrenched the electric system even deeper. The fourth section will shortly elaborate upon the further as well as current entrenchment of the electric system.
The results will be discussed in the following chapter; this involves thematic and theoretical discussion, as well as some ideas on the use of the insights for the modern problems seen in energy systems.

3.1 The Affordances and Constraints of Electricity

Whole textbooks are covering the physics of electricity and electric phenomena, the specific aspects of electricity and its history related to discoveries or electric engineering. This section shall give a short insight into the importance of physical aspects of electricity for this thesis.
Electricity in general is the displacement of different charges on atomic scale and has many adjacent phenomena. Electrostatic phenomena, for example, are known since Antiquity—although back then they were not properly separated from magnetism—and deal mainly with the study of charges that attract (opposite charge) or repel (same charge) other charges. Since the separation of charges requires physical work, the opposite is the case for discharging a connection: thus, when objects with different charges are connected using a conducting medium, a current of charges flows in between to equalize the different electrical potential. During this process of equalization energy is transformed; depending on the type of application, this may be, for example, heat, light, or motion. But also the modulation of these currents allows for purposes, for example information transmission in analogue form such as the telephone, or in digital form such as the telegraph or the internet. Other applications of electricity in form of electric currents are light, heat, motive power, electrochemistry and in modern times also electronics. Although Smil (1994) mentions that all forms of energy are not only quite important for humanity and any attempt to create an hierarchy is thus impossible, but also are they deeply interlinked. Nonetheless given our current knowledge, electric power is probably still the energy carrier with the largest variety of applications.
When electricity is transmitted, generally, the further the distance, the more losses occur. The degree of loss with constant power differs with the voltage of the connection, where higher voltage means less loss[10]. This applies for direct current (DC)

[10]Electric power can be calculated by the formula $P = U \cdot I$, where P is the power, U the voltage, and I the current. With constant power the voltage is inversely proportional to the current so

technology as well as for alternating current (AC) technology. For transmission with identical voltage and distance, DC is more efficient since AC involves losses because it generates electromagnetic waves due to the alternation of the current. As will be described later, high voltage AC systems prevailed in the early 20th century over high voltage DC systems and shaped the path for our current power system based on a hierarchical structure of AC networks with different voltages. For further information and developments of the (nowadays increasingly important) technology of high voltage direct current (HVDC) transmission, see Arrillaga (1998).
The whole system surrounding energy, from generation or acquisition to the final application, can be generally divided into three distinct parts. For electric power systems, these are (i) the generation of electricity (by transformation from other energy carriers), (ii) the transmission of electric current (via conductive materials), and (iii) the application of electric energy (in an appliance such as a light bulb). But the same can also be applied for many other systems; distribution of coal for power plants, for example, is harvested in a mine, transmitted via freight transport and finally applied (as it is transformed or used) in combustion processes. A little more generalized, the same scheme accounts also for information exchange, movement of physical objects and many other things in our world. In the following case-study, electricity is treated in this tripartite structure.

Figure 3.1: Tripartite structure of energy systems.

From a technical perspective there are a few more things to look at in the electric power system: despite the affordances of electricity which were mentioned earlier, this phenomenon also comes with constraints. Generally, an electric power network has to be levelled so that all appliances get as much power as they need without exceeding their range of operation and thus breaking it. The levelling can be obtained either on the supply-side in terms of more or less generation, or on the demand-side with more or less usage of electricity. This gives an immediacy to electricity as maybe the most important constraint: as so often in technical systems, input equals output; a stable flow of an appropriately-sized electric current needs to be guaranteed to make the system reliable and usable in a technical context. This posed big problems in the beginnings of hydroelectricity and reoccurs nowadays in intermittent renewable energies. These problems can be coped with, for example, storage technology: however, devices for direct storage for electrical charge (such as capacitors) have a low energy density and is still now not attractive for larger energy volumes. Instead, for storing large amounts of electric energy conversion into other forms of energy, such as for example chemical energy in forms of batteries or potential energy in forms of pump-storage plants, is more feasible. Large

that an increase in voltage decreases the current: $U \propto I^{-1}$. The total power losses are first of all related to the strength of the current itself, and only secondly with the type of the current, whether alternating or direct.

scale demand-side levelling is virtually non-existent but might be increased in the future due to adoption of smart meters. More about this topic will be discussed in section 4.3.

Another highly relevant aspect of electric power systems is the economic component. Generally, some economically relevant production facility that always runs on full capacity—and thus has a 100% load factor—is the most economically viable because the investment cost can be spread over the longest possible period of working hours and thus the maximum possible output: simple economies of scale. Therefore, power plant operators try to increase usage in periods of low sales to increase the load factor, and try to inhibit usage in peak periods to avoid the necessity to install a higher capacity. This relationship of economies of scale accounts for both the input and the output of generating facilities: if the input energy carrier, such as wind or potentially also coal, is not constantly available, the output will also be intermittent and can not be sold. To avoid this situation of a lack of input, a sufficient stock and refill of fuels has to be available and stored, so that there is a stock of input. Alternatively, also storage technologies on the output-side may be implemented, which might be able to store the electric power output from various sources. On the other hand if the facility does not run on full load, so that there is potential supply for electricity but no usage, the generation has to be either stopped or regulated—and thus generates less or no income—or stored, and can provide a slightly smaller income later due to conversion losses and management efforts.

As further explained in the following sections of this chapter, these two aspects of immediacy and load factor are the major factors around which the internal drivers of electric power systems evolve.

To close off this chapter, the electric power system, as established in the last decades of the 19th and the first decades of the 20th century, shall be put in a context comparing them to the affordances and constraints of the power systems existing before; an illustration of the following elaborations can be found in Figure 3.2. From a spatial consideration, electricity was able to decouple generation from application by means of thin immovable wires ranging from a few hundred metres with early low voltage transmission to a few hundred kilometres with later high voltage transmission; in contrast, earlier systems required either movable, and thus dangerous and range-limited parts such as belts and pulleys in motive systems, or a direct drive for the machinery. Furthermore, the type of power used influenced considerations for a location, as water power could obviously only be developed at places where a lot of water passed a high altitude on a short stretch, while industrial steam power was preferably used close to railway lines or canals for cheap restocking of input fuel. In this sense, steam power was not reliant on natural features anymore, but instead on man-made infrastructures. Also the application of electric power is possible because of man-made infrastructure; however, due to the compactness and—by now—ubiquity of electric power lines, the distribution seems more affordable than with any other source of power. Also in realms other than motive power, for example lighting, there were high managerial or infrastructural dependencies: a necessity to possess and light candles, to always refill oil lamps or to light gas lamps fuelled via pipelines. In electric power systems all these considerations could be ignored to an increasing extent as long as there was a connection to the power network, as well as if the managerial effort of restocking and levelling the system could be outsourced.

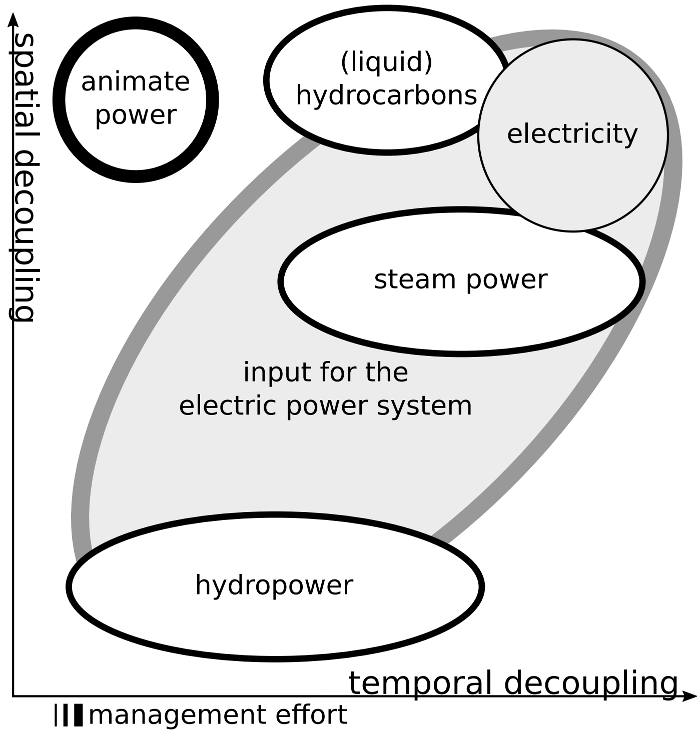

Figure 3.2: Temporal and spatial decoupling of energy systems. For electricity, the introduced concept of scaffolding can be seen during different life-cycle phases from subsection 2.4.1.

Despite the seemingly high spatial decoupling of energy systems from natural or man-made structures over time, the dependence could not completely be eradicated; neither did this happen for the temporal limitations, as hardly any electric energy is stored but instead transformed when needed. However, compared to dependence on seasonally, or even hourly differing water flows, or a constant inflow of primary fuels, the activities and the responsibility of managing and coping with these fluctuations have been outsourced to the electricity provider already in early electric power networks. And even before that, the effect of outsourcing management of power sources can be observed, such as in the early 19th century when in large-scale industrial water power developments the responsibility of providing a constant flow of power was provided by, or passed towards, a managing company. However, in the last decades a trend towards highly fluctuating renewable energies can be observed; this development may seem surprising given the facts stated so far. It might be explained by environmental issues related to fossil-fuel-dependent power plants but also the economic competitiveness of renewable energies in combination with higher sophistication in power network management and levelling technology. This strong separation via physical, administrative and even legal factors between generation, distribution and application of electrical energy is as big as no other energy system before. These factors result in an overall system that is stable and reliable, mostly because of the stability of the input feed and eventual levelling efforts.

It is furthermore the goal of any provider of especially commercially used power to keep the stability of the system sufficiently good for the customers.
However, all these advantages mentioned are a result of long learning and development processes, and numerous innovations. So for reading the case-study or any historic material, we have to keep in mind that views or ideas on electricity in specific, but also technology in general, necessarily have been different at other times.

3.2 Technological Development towards Electric Power Systems

The previous section showed, among other things, how important electricity and its major applications are to modern humanity; the section set the frame for the further focus on technology. Major advantages and constraints of the system which shaped the pathways of inventions and developments surrounding electric power systems have been described. This pathway shall be elaborated upon in this section, though a precise account or detailed timelines of inventions and developments are not part of this elaboration. Rather it deals with selected scientific advances, inventions and the rough sociotechnical surroundings, that allowed and shaped the introduction and invention of new technologies leading to the first electric power systems at the end of the 19th century. For examples on detailed timelines, see among others: Bowers (1982) or Dunsheath (1962) for electricity and the resulting power system, Hunter (1979) and Hunter (1985) for industrial water and steam power in the United States, or Strandh (1979) or Usher (1929) for technical developments and inventions.

3.2.1 Energy and the Start of the Industrialization

People made frequent use of fire already over 300 000 years ago, with the first domestic uses being probably more than 800 000 years before our time. It had a profound effect on hominin societies, as it did not only provide heat and light and the related benefits, but also allowed to consume a larger variety of food by employing cooking techniques and also making food more durable by smoking or easier drying. Much later, more sophisticated agricultural societies extended their use of external energy with animate prime movers in forms of working animals, mostly working on the fields or for irrigation (Smil, 1994; Strandh, 1979). Even long before our modern society emerged, wind and water mills were developed and used to mechanize the labour intensive process of pumping water or milling grain and thus saving many hours a day for other activities (Strandh, 1979). In some regions of China, even natural gas was used for heating and light (Smil, 1994). All these developments were supplemented by tools and devices to transmit the power from the generating source to the point of application, for example harnesses, treadmills or gears (Strandh, 1979; Smil, 1994). This short account of preindustrial energy use already provides good insights into the reasons for further development of energy in society: increasing efficiency, and thus producing more output in a shorter period of time—at the same time, the range of possible activities becomes broader, security is increased and thereby external risk minimized.

By the end of the Middle Ages a wide variety of applications besides flour-grinding found assistance in the usage of—depending on the local circumstances—hydro or wind power: for example sawing wood, crushing ore, smithing, lifting heavy objects, tanning leather, drawing wires, or pumping water (Strandh, 1979). When, in England, the Industrial Revolution was initiated by mechanization of tasks that previously involved human labour, more motive power was necessary. Therefore, in the latter part of the 18th century even more animate power came to be gradually replaced by waterpower, which was the main source for motive power for around a century.

Although the first commercial steam application, a steam pump intended to pump water out of mines[11], was manufactured by the end of the 17th century, it was not adopted widely until the early decades of the 19th century. In the beginning it served mostly for pumping water out of coal mines, though it was a very unreliable and had a bad efficiency (Strandh, 1979). However due to a lack of scientific and technical knowledge, steam technology developed slowly[12] and further improvements were often hindered by patents[13]. The first commercial rotary motion steam engine was developed in the late 1700s (Strandh, 1979), but, for example, due to the availability of good hydropower sources, in the US it was not until the mid 1860s that steam power became more common. Steam power at this time was still twice more expensive compared to a good hydropower site (Hunter, 1979).

3.2.2 Hydropower

Before steam, water was the most important prime mover, and so manufacturing communities settled and evolved around good locations for hydropower development. One such example is the famous town of Lowell, Massachusetts, which became a role model for similar undertakings across America (Hunter, 1979). Those sites were developed at falls or sufficiently steep slopes and preferably a site not far upstream, where a dam could provide opportunities for power management during the day and the season. All the surrounding land was bought up by usually one interest group that developed access to waterpower using canals or later pipes and then sold or rented out the land to interested investors who also had to pay for the provision of waterpower. In these sites much experience with hydraulic supply systems and water management including dams, resistance in pipes and seasonal

[11]Although the first working steampump was developed in England to pump water out of mines, another unsuccessful prototype for a steam pump was developed at the same time in Germany to pump water for a fountain (Strandh, 1979).

[12]The first scientific document on steam appeared in 1824 and was written by Sadi Carnot, but was too abstract, and thus not understandable by engineers. The development of steam power came to be influenced by science only in the 1840s with publications from Joule, Clausius and Kelvin (Strandh, 1979, p.125)

[13]Two prominent examples are (i) the first working steam pump, patented in 1698 by Thomas Savery, and extended from a 14 year to a 35 year protection period (Strandh, 1979, p.117), as well as (ii) James Watt's invention of the first steam engine with an external condenser, which led to highly improved efficiency. It was patented in 1769 and extended in 1775 to expire in 1800 (Strandh, 1979, p.120). As Smil (2010, p.53) notes, "Watt refused to work with high pressures [so that] any developments of pressurized engines had to wait for the expiry of his patent. Once that took place the progress of mobile steam engines both on water and on land was fairly rapid".

water management was gained; this built up the main knowledge for the industrial use of hydroelectricity that quickly emerged at the end of the 19th century (Hunter, 1979).
Another important scaffold for the later development of hydropower was the invention of the water turbine in 1824 which had great success in France and only made it to the United States by 1842. It had an efficiency almost twice as high as earlier technology and allowed a more stable energy flow because it could be submerged in water (Hunter, 1979). A sequence of further developments was made on the waterwheel in the United States, including the invention of the Francis-turbine and the Pelton-wheel, which are two of the main construction schemes for modern hydropower turbines. Mainly because conditions were fairly uniform where the main industries were located, and the mathematical knowledge for customization of turbines was lacking, the manufacturing industry for turbines developed towards mass-production for small- and medium-sized powers (Hunter, 1979). Until the 1880s, when the rise of hydroelectricity demanded bigger and more efficient turbines, this "cut-and-try" approach which led to many advancements in efficiency had to be given up. In contrast due to different geographic conditions, the European market for hydropower was not as uniform as the American market, so that because of the customization necessary, and despite cheaper labour and material cost, turbines were around 50% more expensive than their American counterparts (Hunter, 1979). Both, the theoretical knowledge achieved in Europe and the inventions made in the United States were crucial for larger hydropower installations in the era of electricity.

3.2.3 Steam power

Watt and Boyten's first commercially successful steam engine[14] that could produce rotary motion was developed and sold in the last decades of the 18th century, and slowly started a new era. When their patent expired in 1800, many improvements and new applications showed up (Smil, 2010). The first steam-driven land vehicle was successfully tested in 1801, and the first truly movable prime mover was invented in 1804 (Strandh, 1979). Both developments inspired other inventors to test such vehicles on cast iron rails (Smil, 1994), which would offer a much higher efficiency of transmission towards traction because of the bad road quality. These developments, in turn, led to the railway system which grew rapidly after the 1830s and opened whole new opportunities for freight transport, which had to be done by horse carriages or waterways until then (Smil, 1994). This drastically increased the size of potential markets for investors and thereby opportunities for expansion, but also competition for factories which led to even more rationalization and efficiency-improvements in the industry (Hunter, 1979).
Starting from the 1830s, steam engines also supplemented hydropower in existing installations. Although at first not very favourably greeted by customers, steam

[14]Part of their big success was based on their revolutionary business model. Since customers were generally skeptical about new inventions and would rather install a system that proved worthwhile on other sites, Boulton and Watt leased their steam engines in a way that they only asked for the price of the fuel savings compared to a Newcomen engine—the first rather reliable steam engine—of a similar size (Strandh, 1979). In this way their customers did not take any risk of installing an inferior technology.

power served as an alternative to upstream storage reservoirs for providing customers with the contractually-assured power during droughts; until the 1850s some of those early adopters had grown so much that, by then, they relied on steam power primarily and used water power as a cheap supplement (Hunter, 1979). Already during the 1850s there were more industrial centres located in or near big cities, since cheap and abundant workforce and proximity to the urban market was often given preference over cheap power. By the end of the 1860s the choice of a prime mover accounted for not more than five to ten percent of the total costs for production, so other considerations on location and process, such as water usage, process heat, explosion hazards, or dirt became increasingly important. Even the industrial centres that emerged at sites suitable for waterpower development were starting to be supplemented with steam power througout most parts of the year (Hunter, 1979).
Steam turbines—the technology utilized by most modern power plants working with combustion—were long doomed to be unfeasible, mostly because of material constraints: there was neither a construction which could supply steam in high enough pressure for reaching appropriate efficiency, nor could the high rotary speeds resulting from this pressure be reached with any known materials (Strandh, 1979). Nonetheless, after many years of development, a reaction turbine with six to ten thousand rotations per minute was patented in 1878. In the 1880s de Laval and Parsons independently improved steam turbines, and in the next decade a large variety of steam turbines was built. By 1910 steam turbines were more common than steam engines for electricity generation (Strandh, 1979).

3.2.4 Electric Technology

Static electricity is a phenomenon that has been known since Antiquity. Back at the time they knew that rubbing certain materials against each other caused attraction of certain light bodies (Bowers, 1982). Today we can observe this effect for example from rubbing a balloon against cotton clothes and then holding the balloon close to our hair. Systematic research on electrostatic and magnetic effects started in the 16th century and later involved mostly metals and chemicals. The studies of current electricity evolved from this research and was initiated by Alessandro Volta in 1800. Volta invented the voltaic pile, an apparatus capable of producing a continuous electric current from chemical energy (Bowers, 1982). During the first years of the 19th century, electric arcs, which were later applied in the first electric lights, were discovered, as was the capability to separate water and other substances by electric current: an early development of electrochemistry (Bowers, 1982).
The study of electromagnetism slowly emerged early in the year 1820, when physics professor Hans Christian Ørsted discovered that a floating electric current could deflect a compass needle. Via a variety of other advancements this led to the discovery of magnetoelectric induction by Michael Faraday in 1831 (Bowers, 1982) and the first magnetoelectric generator invented in the year after. Possibly the first electric power generator was installed in 1842 in a company working with electroplating (Fischer et al., 1992). But size and efficiency were largely limited by the necessity to use large permanent magnets. This changed when, in 1866/67, Wheatstone and Siemens simultaneously invented an electromagnetic generator, employing the effect

of induced electric fields to substitute those magnets (Strandh, 1979; Bowers, 1982). Two decades later, at the end of the 1880s, alternating current technology had some fundamental advancements as well, and became a viable alternative for the high losses that the used low-voltage direct current brought for transmission over long distances[15] (Strandh, 1979; Bowers, 1982).
Although electric light was occasionally used in factories, public places, theatres or lighthouses, the beginning of the electric era is often said to be around 1880, with Thomas Alva Edison's invention of a durable and relatively efficient incandescent light bulb. More importantly, he also invented necessary components to integrate various electrical technologies into a generally applicable and installable system of generation, transmission and distribution (Strandh, 1979). Later, with this development and despite all the earlier electric technologies, the electric era started; applications of electricity and their impact on society will be explored in a later section.

3.2.5 Science, Technology and Engineering Practice

Most of the achievements in water and steam power until the end of the 19th century had been made by engineers and practitioners, without or only with modest scientific background. Modern scientific interest in mechanical principles slowly emerged during the late 17th century, among others via the works of Sir Isaac Newton. Also the field of thermodynamics, and with that the scientific context for steam power, was only scientifically explored starting in the 1820s, although the first applications of steam power had existed for over a century by then (Strandh, 1979). With these insights from science it was subsequently possible to base steam power engineering more on science than on practical experience, and thus to develop and improve technology gradually. The invention of the first modern water turbine in the 1820s—which actually resulted from a competition of a French engineering society—was greatly facilitated by advancements in mathematics and fluid mechanics (Strandh, 1979; Hunter, 1979).
Actually, by the time the steam engine was invented, there was hardly any opportunity to obtain engineering knowledge by formal training or education. Strandh (1979) suggests that millers and tradesmen can be seen as the early mechanical engineers building up their milling system, maintaining and refining it. Often during the 18th century, the creativity and inventiveness of these craftsmen was more advanced than the surrounding engineering practice or possibilities, so that necessary precision or material strength were often impossible to obtain (Strandh, 1979). Only towards the end of the 18th century, regional centres of advanced engineering practice or knowledge developed. Those centres, such as the workshops of Boulton

[15] It was well-known by practitioners, that a higher voltage involved lower losses in the power transmission. The first high-voltage direct current (HVDC) transmission was achieved in 1882 over 35 miles distance (Arrillaga, 1998); after 1889, HVDC gained importance, however by connecting generators in series to increase the voltage, it was not as flexible as the alternating current solutions for which transformers provided easy solutions to change voltages. Also the introduction of the steam turbines rotating on high speeds made the application of direct current generators and their serial connection more difficult. Hence, HVDC transmission was often only taken up again for specific purposes but until now still not has the systemic status that alternating current technology has (Arrillaga, 1998).

and Watt, where they manufactured and occasionally improved their steam engine, attracted and inspired many young and talented people (Strandh, 1979). By the middle of the 19th century a higher sophistication of the technology and better tools led to a specialization from universal towards specialized workshops for e.g. steam engines or machine tools (Hunter, 1979). Around 1800 in France and Germany the first formal engineering schools were established. But these mainly served to educate civil or military engineers entering the state-service, and admission was often exclusive and only for the privileged (Lundgreen, 1990). Most of the engineers in the private sector received their training in classical machine shops, and general university education without connection to state-service was initiated only in the second half of the 19th century (Lundgreen, 1990). In England and the United States such state-run academies did not exist, and institutional education for engineering only started in the late 19th century (Lundgreen, 1990).

As mentioned above, as opposed to Europe, in the United States engineering and technical product development during most parts of the 19th century was driven by a searching cut-and-try process rather than by scientific reasoning (Hunter, 1979). Until bigger and more efficient turbines for hydroelectric power plants were needed, this way of manufacturing led to many technical improvements towards high performance at low cost. So when, around the 1850s, more turbine manufactures were starting their business in an increasingly connected market, these processes lead to, on the one hand, the reduction of difficult features—such as those that necessitated hand fitting or close accuracy—and, on the other hand, a system of high volume production involving standard dimensions and parameters with interchangeable parts (Hunter, 1979). However, a big market with many competitors also lead to a situation that was unclear for potential buyers, and ultimately to "heavy advertising and exaggerated claims of performance" (Hunter, 1979, p.349). Over some decades this competition led to a highly reduced amount of suppliers. Part of this process was the first commercial site for independent power measurement in the US, which opened in 1869 as manufacturing sites lacked not only equipment but also know-how for accurate testing of efficiency. This not only helped increasing overall efficiency but also applied coercive pressure onto companies (see DiMaggio and Powell, 1983) towards adopting certificated efficiency claims, and later towards guaranteed performance being part of the sale contract (Hunter, 1979).

It already became obvious that the geographical, cultural, and thus technological decoupling of Europe and North America had a relevance for technological advancement; for example with respect to the development of the water turbine. To a slightly lesser extent this accounts for developments within these regions as well. However, it cannot be emphasized enough that through the integration towards a common market—first by means of transportation, and later by communication infrastructure—not only efficiency and rationalization were fostered, but diversification and the development of niche technologies might be limited at the same time.

3.2.6 Transmission and Control Technology

In the large hydropower sites of the 19th century, a complex system of canals, pipelines, locks, gates, and dams developed over time. By the middle of the century it

was furthermore supplemented by devices for measuring the hydropower consumed. These components allowed not only relatively precise control over the needed amount of power in a specific moment, but could also make up for seasonal fluctuations in the natural water flow by using a dam or larger millpond (Hunter, 1979). The direct, hydraulic transmission of flowing water proved to be more efficient and feasible than one large generating turbine supplying all different factories with their rotary motion; and an individual adaptation to the power needs would not be possible otherwise. Instead, the rotary motion was generated by each of the factories theirself, at first with an overshoot wheel and later with turbines. This rotary motion was transmitted to the respective devices by a complex system of “shafting, pulleys, and belting” (Hunter, 1979, p.112) that replaced the previous system of direct connection from prime mover to machine via fixed gears and wheels. Smaller applications using minimal power could be driven by water engines using the pressure of floating water; however, these were later forbidden by many local authorities (Hunter, 1979).
This connection and distribution system was basically the same as for steam powered factories so that supplementing or substituting the power during droughts or for peak loads was a relatively easy task (Hunter, 1979). A shift towards steam power thereby, in general, required no effort of organization or redesign (Grübler, 2003) except for the management of constant fuel input. However, the many interconnections and transmission lines for motive power posed a danger for workers, and an efficient power distribution led to inefficient factory designs. Besides, the supply of raw materials was sometimes hindered (Grübler, 2003), and since the system did not allow for different power supply for individual machines, the whole factory had to stand still if one single machine had to be maintained or fixed (Nye, 1990).

3.2.7 Social Developments and Surroundings

Industrialization had a strong effect on society: more mechanization in factories, mills, and also farms brought an ever-increasing efficiency. This increasing efficiency was accompanied by higher revenues, which in turn allowed higher wages and reductions in work time. During the 19th century, wages therefore increased drastically, and a maximum working day of eight to ten hours, with six working days per week became common[16] (Grübler, 2003; Hunter, 1979). The surplus money could be spent on additional belongings which in turn also became cheaper due to mass production, and the gained time could be spent on leisure activities such as shopping, theatres. In a weakly globalized economy like this, increased wages were to a large extent also spent on locally produced goods and services, and therefore benefiting the employing companies directly in a closed economic system.
The economy based on mass production originates in the increasing efficiency that results from mechanizing and standardizing labour. Together with the interconnection of markets by the railroad system and the related market competition, this allowed for mass production and consumption systems, which at first facilitated the

[16] Interestingly, waterpower became more competitive compared to steam power when working hours were reduced. On the one hand, the effective utilization time of steam engines decreased and thus raised the hourly cost, but on the other hand, the decreased working hours allowed waterpower developments to have more idle time recharging their millponds with power and thus decreasing power outages or the necessity to supplement with steam power (see Hunter, 1979)

rise, and then later the fall, of waterpower (Hunter, 1979; Grübler, 1990). However, only after the invention of assembly lines in the early 20th century, with purely rationalized and optimized—via the use of smaller electrical engines—production lines that manufactured identical products, mass production was really a part of the economy (Hounshell, 1985; Grübler, 2003). This development of increasing efficiency also affected agriculture, leading to combined push- and pull-dynamics. Hereby, rural areas became less attractive while urban areas became more attractive. This led to strong urbanization, with more people moving to growing towns or cities. Though, because of rather bad transportation options, focus was still upon the local neighbourhood, which not only provided some options for entertainment and shopping, but also needed to be supplied with goods. Therefore, for finding a location for a factory, transportation cost always had to be weighed with power and labour cost, so that during the 19th century increasingly more manufacturing industries were located away from the sites of cheap water power, towards the sites of cheap workforce and a big market (Hunter, 1979).
On the flip side of the medal, the industrialization was occasionally causing public discontent and unhappiness as people were afraid that the new technology would be taking their jobs. So in the earlier decades of the 19th century, when more factories close to urban environments were equipped with steam power, there was occasional rioting resulting in the destruction of the technology seen as the culprit of their grievances, such as automatic looms and steam engines (Strandh, 1979).

3.2.8 The Scaffolds of Development

The presented developments and stories provide a basic but concise introduction into the history of non-animate energy before the large-scale appearance of electricity. In this section, this information should be bundled, summarized and put into the developmental context as described in the previous chapter.
Hunter (1979, p.482) mentions three main reasons for the decline of direct-drive waterpower: (i) "the progressive industrialization of the economy," (ii) "the extension and completion of the railroad network nationally," (iii) "and the urbanization of manufacturing". Fascinatingly, in particular the transportation infrastructure at first scaffolded the development and increase of direct-drive water power, while facilitating the growth of steam power: as the first canals were built and used for transportation of goods, steam power was yet too expensive for mass production and therefore not a competitive alternative to water power (Hunter, 1979). Thus, at first, water power profited from an increasing market due to cheaper transport. This also accounted for the early railway lines which facilitated growth of hydropower sites as it allowed the fabrication and marketing of an even larger amount and variety of goods, with short transportation times to an increasing market, while it was possible to exploit the cheap hydropower to the full extent (Hunter, 1979). However, while the railway system was further developed and hence increased the market potential even more, at the same time steam technology improved not only externally but also inside the system of water power: it served as a source for emergency power (and later surplus power), as well as in the application in the railway system. In this way, the steam-powered train system not only scaffolded growth of two sub-

sequent systems of motive power supply by increasing the market size, but water power also shovelled its own grave by employing steam technology as an auxiliary power source. Besides all the other applications of steam power, providing valuable learning in a manufacturing context, it was also used to acquire some redundancy and resilience at hydropower sites, while both power systems soon became a hybrid technology.

Water power was soon unable to compete with the supply stability of steam power. The increasing importance of trains for freight traffic "created a competitive situation in which the uncertainties of a power supply resting upon falling water became increasingly unacceptable" (Hunter, 1979, p.484). In normal years—despite a less smooth running of machinery—this usually had not such a big effect because of the proper management via dams and flow regulation, but anomalies such as an exceptionally dry summer pushed adoption of steam power even in water power sites as early as the 1830s (Hunter, 1979). Also the demand for more power—especially the constant supply of peak power which resulted from melting snow in the mountains—drove water power sites into the adoption of steam power. This quickly turned some of them into industrial areas, more dependent on steam than on water. Later, the cost for steam power came to be on par with that of water power—which was the case in the late 1880s if exhaust heat was utilized—direct drive water power had hardly any economic power left (Hunter, 1979). Incidentally, this was around the same time when large electric systems started to appear so that some direct drive water power sites were changed into hydroelectric power sites. Since in the beginning, electricity only provided for lighting, water power was a cheap source of power for a bright city, and with the occurrence of AC technology, also remote water powers could be utilized to power cities, allowing a quick reappearance of these large hydropower systems with a slightly different purpose and layout (Nye, 1990; Fischer et al., 1992; Bowers, 1982).

However, water power also had some advantages that still made it the major driver for some industries: it was clean, provided process water that could be used, and it posed no explosion hazard. While by 1870 many industries were still mainly reliant on hydropower, by 1900 the paper and wood pulp industries were the only ones relying still primarily on water power, which is mainly because of the need of lots of water for the respective process making a location close to a big water source mandatory anyhow (Hunter, 1979). The flour grinding and milling industry utilized steam power and water power to approximately equal shares at that time, maybe because of the danger of explosion for these products, and the remoteness of the production locations of flour. Fascinatingly, in every sector, despite the iron and steel industry and the lumber and timber products, new water power resources were still installed during these thirty years. Water power installations in the US increased by almost 53%, while 619% steam power were added in the same time (Hunter, 1979).

Other important scaffolds for improvement and development of direct drive hydropower, besides the transport infrastructure, were (i) the prize awarded in the 1820s by a French engineering association for a submersible waterwheel (Strandh, 1979; Hunter, 1979); (ii) the publication and engineering science infrastructure that brought the ideas of the turbine to the US in the 1840s; (iii) the large direct drive hydropower sites in the US that focused on rationalization; (iv) the cut-and-try manufacturing culture that focused on economic efficiency rather than on scientific design; and, (v) the institutionalized testing of waterwheels starting in the late 1860s (Hunter, 1979).

In turn, hydroelectricity was scaffolded by all these learning processes, though with hydroelectricity, any efficiency-improvement meant more profit for the operators so that the engineering culture even in the US twisted around towards larger, bigger and better turbines (Hunter, 1979). The experience gained with measurement and management of large water resources benefited the early hydroelectricity developments. But even more so, it contributed towards a large system of hydropower installations around the 1920s. This system was not only used as a cheap source of electricity, but also to level and regulate the electric power system when the interconnection of grids increased the system size, and the previously used direct-current batteries could not be used anymore (see Fischer et al., 1992). On the other hand, hydroelectricity earlier also facilitated the application and improvement of alternating current technology, since opportunities for development of hydroelectricity were the first occasions when long-distance alternating current transmission lines were tested and applied (Strandh, 1979; Nye, 1990) and thus among the first applications of these systems, providing valuable learning experiences for the rise of alternating current for general transmission.

On the other hand, steam power was scaffolded by the cheap and easy accessibility of coal in the beginning, and the later necessity to pump water out of the ever deeper mines. Again, a feedback loop emerged since these pumps required the coal that they were supporting the harvesting of. As Strandh (1979, p.118) notes, in the mid of the 18th century, when steam engines were existing but had a high fuel consumption "[it] was said that an iron-mine was needed to build and maintain one, and a coal-mine to keep one running". The invention of a system to transform reciprocating into rotary power by James Watt in 1781 allowed the steam engine to enter many new fields of application that were developed in parallel, or used with animate or water power, such as the automated weaving looms showing up around the same time, but also cranes, mills and other facilities (Strandh, 1979). Also traction was made possible by this: Based on the first experiments with rails, the railway system as an interurban infrastructure probably originated in poor road quality and the low rolling friction. Back then, this was especially relevant, as only horsewagons[17] were used for road transport—which railway transport could easily supersede in capacity and speed—, while heavy freight was transported by ships. The result was an interconnected market of increasing distribution networks and faster supply of goods.

Later, the development of the steam turbine was highly facilitated by the long learning experiences with water turbines. But even more so—since it originated from the development of a milk separator—by the larger markets for agricultural products due to efficient traction that lead to an increase of technology in agriculture. The steam turbine was already more applied within electric power installations than to provide direct rotary motion, and so again—just as in the case of AC technology—

[17]Interestingly, the first railway carriages still likened horsewagons in design and appeal; they contained many separate, small compartments with separate doors rather than—as common in modern trains—aisles going through the whole length of the carriage (Strandh, 1979).

the electric power system incorporated and improved a new technology.
Besides all that, the development of the surrounding sociotechnical environment of the developing power systems and of the transmission infrastructure was highly influenced by already existing features. Those shaped the context, and thus determined whether a technology could be adopted, and to what extent this could happen. For example, the different orientation of the axis of the newly introduced water turbine, compared to the previous installation of the water wheels, led James Francis to modify the turbine layout in a way to allow the old axis to stay in place (Hunter, 1979). The accompanying redesign led to quite some improvements on the technology itself. Similarly, the Pelton wheel was developed from the old water wheels that were more efficient than the Francis turbines in the locations with a high head of water and thus high water velocity (Hunter, 1979). In contrast to this, the predominant flow-direction in turbines—whether inward or outward-flow—rather limited innovators creativity, and later a reversed flow brought some further designs and advantages. And then, finally, there is also the common example of factories not adopting steam technology because it would not fit into the factory buildings and thus require a complete reconstruction of the respective buildings.

3.3 Bringing the Magic to the People: the Electrification

When the first public electric power supply was introduced in the early 1880s—commonly seen as the start of the electrification—there were numerous technologies which had used electricity before. Those technologies set a frame for the electrification, they provided valuable and important learning experiences for electric technology, for the practitioners, for the devices and machines to generate electricity, and for some applications of electricity; but most over all these technologies created a certain public attitude towards electricity: it was some kind of magic.
This section largely deals with the societal impacts of the electricity. It is not completely chronologically structured but looks at thematic clusters: it starts with the early electric systems not necessarily suited for mass consumption that were highly valuable for learning and formed the basis for the rapid electrification of urban areas later on. Following this is an account of the evolution of electric grids and their different development stages and societal effects, as well as the use and effect of electric power in industries. Finally there is an account of the social meanings and results of the electrification, before the section finishes with the late electrification of the American countryside.
Unless otherwise mentioned, this chapter focuses upon the United States of America; European developments might have differed drastically, among others due to highly different governance approaches (see Hughes, 1983).

3.3.1 Learning for Grids: the Early Electrical Systems

Before electric power was sent through the first electric grids there was a long learning curve necessary: large-scale manufacturing of components, proper insulation,

measurement tools, switches and many more devices had to be developed. Based on these presupposing developments as described in this section the first electrical power connections were possible.
This section covers the development of the telegraph, electrochemistry and electric lighting before 1880.

3.3.1.1 The First Large-Scale Electric Appliance: Telegraphs

The only electric technology of general importance before the introduction of electric supply systems was the telegraph. Although first ideas on electrostatic telegraphs exist already many years before the development of the voltaic pile in 1800, there have only been failed or at least not commercial attempts for telegraph systems until 1837, when the first commercial telegraph systems in England and the United States were patented and subsequently introduced. While in England a technology with five cables and needles to transmit letters in a parallel connection[18] was patented by Cooke and Wheatstone, in the same year in the US Samuel Morse developed a system with one only one cable. to transmit letters, he developed and used the nowadays famous Morse code which encodes characters in serial structure based on an intermittent current (Bowers, 1982). However, Morse could not patent his invention in England because it had been published in a magazine a few months before he came there to obtain his patent; a prior publication generally forbade and still forbids patenting in England and many other countries.
Within the next ten years telegraphy gained general importance for instant communication, for example along railway lines. By 1851 the first submarine cable was installed across the Channel, and in 1866 the first cable crossing the Atlantic followed (Bowers, 1982). While in continental Europe the installation of telegraphy lines was driven by the governments, private enterprises drove the early development in England and the US. However, in England the telegraphy infrastructure development was nationalized later because of the high redundancy in urban centres and the low development in the countryside (Kieve, 1973). All connections were point-to-point so that it remained too costly for common people to install a line; despite this, Wheatstone put a great effort into developing the so called ABC-telegraph—a system for the general public that could display the respective letter immediately so that no technical knowledge was necessary (Bowers, 1982).
Bowers (1982, p.38) mentions, that the sudden success of the slightly technically improved telegraph in the 1860s compared to the 1840s was lying "in the new public understanding of the electric telegraph: people know that messages could be sent over the wires, and wealthy people wanted to buy the wherewithal to send messages between home and business or between offices". The importance of knowledge about certain technology and its application is a reoccurring scheme in the electrification, for example for electric light by which people were largely fascinated when they first encountered it. For normal people who could not afford telegraph connections, institutions such as post offices provided the service of sending a message to another

[18] Parallel encoding means that many cables for data transmission are used simultaneously, whereas serial transmission means that only one wire is used. In modern system the same connections occur, but both might eventually have a additional wires for control signals, ground or power transmission.

institution which was then delivered to the respective recipient; still it remained a high expenditure undertaken only on special occasions. Nonetheless, by the 1880s telegraphy was well-known by the public in all areas of the country (Bowers, 1982). Not only did the development of telegraphs have a big impact on society and businesses around the world (see Kieve, 1973), but it also brought the study and science of electrical technology forward. Theoretical advancements were made and practical problems were solved; both helped the large-scale introduction of electric light later: the insulation and connection of wires as well as the manufacturing of those and other components which were also necessary in later electric systems (Bowers, 1982). Many if not most of the important electrical engineers started their career in the field of telegraphy in the mid of the 19th century and gained important experiences with electric technology; these are among others Wheatstone, Siemens, Edison or Thomson. The technical society dedicated to telegraphy soon broadened its scope towards electric technology as a whole (Bowers, 1982).
The invention and developments of telephones during and after 1870s had its roots in telegraphy and changed communication patterns even further. Cable-bound telegraphy eventually got replaced for certain purposes by telephone, radiotelegraphy and e-mail.

3.3.1.2 Electrochemistry

Electrochemistry is the study of "chemical phenomena that are coupled with reciprocal exchanges of electric energy" (Lefrou et al., 2012, p.1). Just as the whole branch of electric science, it had its origins in the voltaic pile, in this specific case from the observation and study of the interactions of electricity with matter (Bowers, 1982; Lefrou et al., 2012). Compared to conventional chemistry it bore the advantage to control reactions precisely by adjusting voltage and current (Lefrou et al., 2012).
Besides the discovery of elements such as potassium, sodium or calcium, and the easy isolation of elements such as hydrogen, also whole industries emerged around the electric manipulation of matter in the 19th century: synthesizing and plating of materials, energy storage and conversion mechanisms such as batteries and early fuel cells, measurement of chemicals, and corrosion resistance. In modern times electrochemistry also serves biochemistry or environmental applications such as separation or recovery of material (Lefrou et al., 2012). The electrochemical industries were—besides telegraphy which did not need so much power—the first to apply electricity on larger scales; by the mid of the 19th century, electroplating as well as the extraction of reactive elements were common applications (Bowers, 1982). In this way it is not surprising that the first electric generator—using four large horseshoe magnets—was installed in 1844 in an electroplating company in England (Fischer et al., 1992).

3.3.1.3 Early Electric Lights: Bringing Excitation and Astonishment

Electric arcs were discovered probably two years after the development of the voltaic pile in 1800 (Bowers, 1982). The discovery was probably made possible by the larger amount of stored electric energy and the higher voltage compared to earlier systems. Basically, an electric arc emerges when electric charge is flowing through the air between two elements made of carbon (Bowers, 1982). The more energy the battery provides, the longer the electric arc will exist; and the higher the voltage, the bigger the distance may be. In contrast, before the invention of the voltaic pile electric arcs were rather instant sparks than constant arcs due to a lower volume of stored energy.

Although the idea of an electric arc lamp seems to be a straightforward step from the discovery of the electric arc, its discoverer Davy subsequently used the electric arc mainly for heat. Still, attempts for creating electric arc lights were numerous, but until the 1870s not successful on a larger scale (Bowers, 1982) for a variety of reasons: in the 1840s the first productive installations occured, but in the early years they still had to be manually readjusted because the carbon elements wore off (Fischer et al., 1992; Bowers, 1982). Also the cost of electricity was quite high so that any general application was not viable until the electromagnetic generator was invented in the 1860s (Bowers, 1982). And as another reason, until the late 1870s only one arc light could be used per one generator (Fischer et al., 1992; Bowers, 1982) which might not have mattered so much since arc lights were very bright, but this circumstance imposed a high management effort to keep many generators up and running when lighting a larger area. Concluding, early electric arc lights were only used in very special circumstances until the late 1870s.

Probably the first of these special circumstance was the lighting of the Place de la Concorde in Paris in 1844, followed by light effects resembling the sun in the Parisian Opera in 1849; in 1852 the first lighthouse was equipped with a dynamo and an electric arc light which was enhancing the visibility enormously (Fischer et al., 1992; Nye, 1990). Within the next decades, more applications of electric light appeared. These were mainly justified by higher light intensity compared to other forms of light, such as gas or oil lamps: as public light on the street, it could light up more area due to the increased brightness and thus lead to reduced crimes and increased public safety (Schobert, 2002). Also, the installation of electric light at railway switches, freight terminals and harbours increased the operating hours and thus economic efficiency of these areas which could not sufficiently be lit with other forms of electric light; hence more goods could be shipped or loaded during one day and operating efficiency could be increased (Schobert, 2002). In 1868 even a construction site in Munich was lit by electricity to allow longer working hours (Fischer et al., 1992).

In 1876 a differential arc light was developed that allowed to power many arc lights with one single generator. This finally helped the electric arc light to a breakthrough, and in the following years many factory halls, train stations, public places, factories and even the climb to the Vesuv were lit by electricity (Fischer et al., 1992). Two years later, the probably first store in the United States was using electric light (Schobert, 2002), attracting many people to simply see the wonder of electric light (Nye, 1990). People perceived any form of artificial light as a supernatural novelty, leaving them astounded and attracted (Nye, 1990). But with more and more installations there was a growing realization that electricity might be better distributed centrally rather than managed in a decentral manner (Schobert, 2002), which Thomas Edison was maybe the first to commercially exploit, as will be described in the next section.

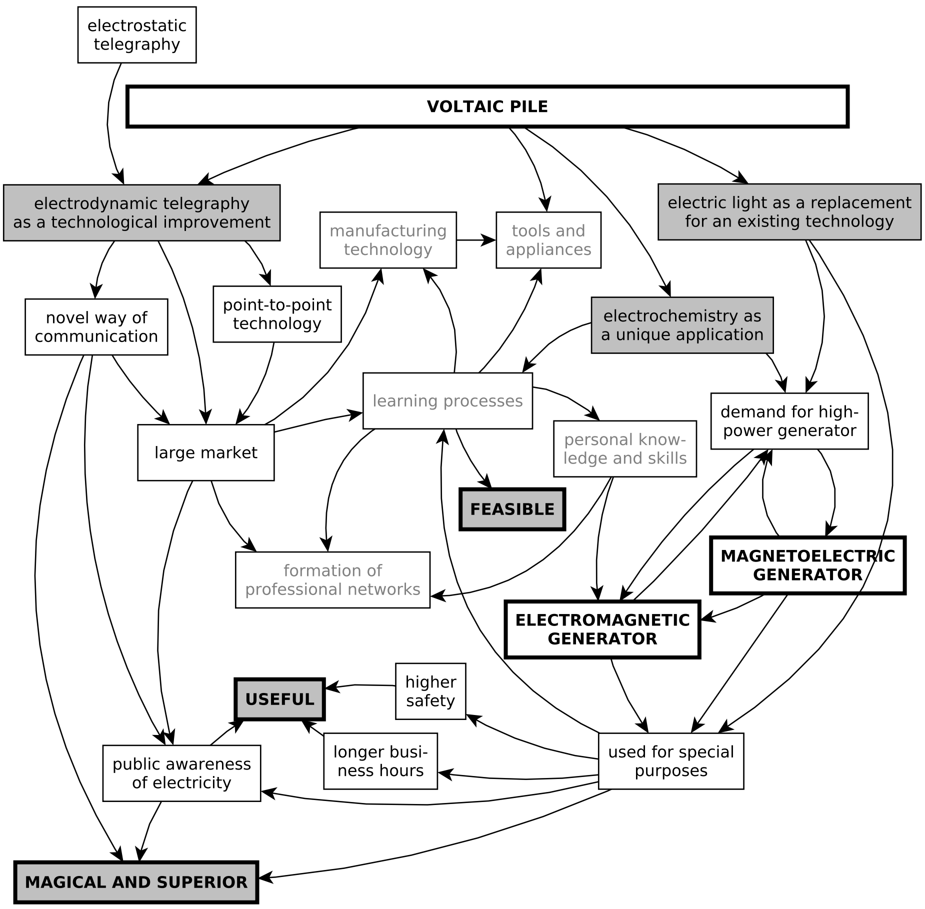

Figure 3.3: Learning processes towards the electrification.

The second main development offering electric light was the incandescent light bulb, also with a technological breakthrough in the late 1870s. That wires became incandescent before breaking from overheating was probably discovered and known by many scholars in the early 19th century; however, low heat resistance and oxidation of the filament posed many problems so that the first proper light bulbs invented in the 1840s did not burn much longer than a few hours (Bowers, 1982). When in the 1870s vacuum pumps got better and the oxidation could thus be limited, many inventors broke ground for electric filament lights. Among these inventors were Swan in England and Edison in America who both succeeded with working prototypes of filament lamps in 1879 (Bowers, 1982). The lifetime of the lamps was gradually increased from a few minutes or hours towards a few hundred or thousand hours within the next years. At the same time, commercial production started and in the United Kingdom Edison's and Swan's companies were united to profit from each other's developments and findings (Bowers, 1982). The next big breaktrough in electric filament lights occured with the increasing use of tungsten around 1910 for better heat resistance and thus longer durability (Schobert, 2002).
Although it was longer in use for special applications, such as spotlights where a high light density was needed, the carbon arc light was phased out and replaced by incandescent light bulbs in that time. However, until now successors of the electric arc light as well as of the incandescent light bulb light our surroundings.

3.3.2 Economies of Scale: the Expansion of Grids

A decentralized system purely consisting of chemical batteries is economically and physically efficient as power is only used when necessary and stored energy ideally does not disappear. In contrast, a system with a generator is not efficient in a decentralized system because when the generator is not running it cannot produce output and therefore profit; also any load below the full power output would also be a loss. These economic inefficiencies can be eradicated when electric power consumption is levelled to a constant state. Since this is often not possible, any increase in network size and any diversification of the consuming appliances helps to increase the load factor and thus profit.
This section deals with the expansion of the electric grids, starting from the first small generators in the early 1880s, that only supplied electricity for very small areas and only during a certain time of the day, towards large regional and unified systems of power distribution in the early decades of the 20th century. The subsequent electrification of the countryside starting in the 1930s is accounted for in a later section.

3.3.2.1 The First Electrical Supply Schemes

Soon after the technical feasibility of electric lighting was demonstrated to be feasible and profitable, complete commercial systems not only for lighting but also for generation and distribution of electricity were sold. Thomas Edison was the first to exploit the market for electric grids on a large scale as he made some additional inventions to facilitate mass production and deployment of these systems, and to divide input and output so that electricity could be used without any technical

knowledge (Bowers, 1982; Strandh, 1979). Although by 1882 electric light already scarcely existed in private houses of the wealthy, shops or on some streets, Edison is often claimed to be the first who sold electricity, or better the electric power system, starting in that year. With these systems the management of the grid and the input could be done by an external company, and electricity was sold to commercial or private customers (Strandh, 1979), though usually only during a few hours of the day when light was needed (Nye, 1990).
But even before this, already in 1879, a first central electricity generating station for lighting the streets was opened in San Francisco (Schobert, 2002) and a few months before Edison's first public supply scheme there had been a similar but water-powered installation in Godalming, England, for public and private electric lighting (Bowers, 1982). Generally, these systems were based on the idea that streets were lit by the electricity of a generator, but every adjacent household could access this power when the connection of their house and the used electricity was paid for. The station in Godalming used water power at first but this proved to be too unreliable for lighting the whole city and thus it became replaced by steam power soon. It was phased out again a few years later because it lacked profitability, in contrast to the Edison systems that remained successful for longer (Bowers, 1982).
During the following years the market tended towards centralization. This was especially caused by reasons of efficiency, load, organizational aspects, and the comparatively low cost of setting up a distribution network (Schobert, 2002). Not only was the feasible distance for transmission drastically increased over the years, but also were different grids connected to increase resilience and decrease management effort—for the first time this happened 1887 in Berlin (Fischer et al., 1992).
The first alternating current power plant and the relating hierarchical distribution system with connections of various voltages were built in 1889 and allowed to have a large and thus technically very efficient centralized plant which was easily accessible for fuel supply but still could distribute electricity very far away because it utilized high voltage transmission (Schobert, 2002). Though, this power plant struggled a lot with technical problems, legal restrictions, and competing and overlapping direct current networks (Hughes, 1983).
When in the following years long-distance transmission from large hydroelectric resources to bigger cities was tested, polyphasic alternating current systems were introduced, and the respective generators and motors improved. The alternating current system slowly started to win this so called *battle of the systems* against the direct current system heavily defended by Edison. For example, he bought a patent for alternating current transformers but did not apply it (Fischer et al., 1992), and Schobert (2002) mentions that the first death sentence executed by electrolusion in the 1890s was part of a dirty campaign of Edison against alternating current.

3.3.2.2 Electric Traction and its Load Management

Although the first patent for driving a streetcar with an electric motor was issued in 1834 to Thomas Davenport, insufficient transmission technology and the lack of generators made it impossible to build a feasible and cost-effective streetcar because battery piles would have to be installed on the trolley. Later, in the 1870s and 1880s, development was highly boosted by the introduction of generators and many new ideas on electricity transmission for streetcars—including overhead wires which are common nowadays—were introduced (Nye, 1990). In 1887 Frank Sprague built up the first commercially feasible electric traction system mostly by combining previously available technologies in a novel way. The Edison General Electric Company bought Sprague's patents, and by 1890 around 90 percent of the two hundred cities with streetcar systems were based on these patents (Nye, 1990). Despite the disadvantage of huge financial investments and legal difficulties, electric traction was around twice as fast as the replaced horse carriages and thus could cover a wider area with the same effort. Furthermore, the risks related to keeping horses could be avoided while at the same time profits were often multiplied upon introduction of the trolley service. Especially interurban networks were highly profitable (Nye, 1990).

Besides the social developments and effects of traction that are elaborated later on, purely economic considerations drove the business of the traction companies. To achieve a higher load factor and thus cheaper electricity, traction companies especially in interurban service soon sold excess electricity during the evenings and at nighttime to small communities along the tracks. These in turn used the electricity mostly for public lighting to polish their image and present theirselves as progressive and modern communities like it was common in that time (Nye, 1990). While in the 1920s for the traction companies the business of selling electricity became more profitable than traction itself, for small communities this was the only opportunity to become electrified. However, in 1935 legislation forced the companies to split traction and electricity sales.

Another means to increase the load factor of electric traction systems was the construction of amusement parks at the end of the streetcar lines. These used most electricity when traction was not at full load, and also they enhanced the transportation demand during holidays, weekends and at nighttime. More information on the influences of amusement centres can be found later on. Important in this section is the fact, that traction companies soon actively sought to increase their load factor by various means, and that this sort of entertainment also developed from the incentive to use more off-peak electricity rather than only for exploiting the population's attraction towards amusement.

Later, in the 1910s and 1920s, more people could afford a car so that many urban streetcar systems in smaller cities disappeared until the early 1930s[19], while interurban systems remained intact for a bit longer (Nye, 1990).

[19]The adoption of cars made transportation much easier and faster, so that many people chose to own a car rather than take the public transport; coupled with bad maintenance and decreasing growth of cities, this slowly drove public transport companies into debts during the 1920s, and many communities could not afford to take over these indebted private systems (Kay, 1997). Those transport systems that did not fail on their own, such as trolley systems in larger cities, became victim of a consortium—organized in 1932 by General Motors as the main shareholder of the Greyhound bus, together with industry partners in the oil, tire and highway sectors—"to buy and shut down America's streetcar systems" (Kay, 1997). On the other hand, Wood (2003) argues, that the replacement by buses would have taken place anyway, because streetcars seemed to be an inferior technology compared to streetcars; in the beginning only in lightly populated areas, but by the 1950s in any part of transportation business. Apparently, protectionism by local governments might even have delayed the replacement process (Wood, 2003).

3.3.2.3 Economics of Large Scale Distribution

Although the market became more centralized in the last decade of the 19th century, there was still a variety of ownership and business models existing. In many towns in the US, besides private generators in stores or factories, a tripartite structure emerged until the turn of the century: at first, one or more private systems for electric power distribution within the commercial centre of the town were set up by some businessmen. They sold electricity to adjacent stores, theatres, bars and occasionally also lit the streets (Nye, 1990). Often a bit later, a publicly financed electric power system was set up to provide light for public institutions and the streets. These systems often suffered from corruption and mismanagement. At last, an electric power systems driving streetcars or interurban railway lines were established. With it came electrification for the communities along the tracks as well as amusement parks and the emergence of specialization of districts within the cities (Nye, 1990).
During the first years of the 20th century however, many of these enterprises failed, were taken over, or merged with others which lead towards a centralization of management and power in electric networks (Nye, 1990). This centralization was partially made possible by the rise of alternating current technology, which had started a decade before and allowed higher voltages to limit losses over long distance transmission. For example, in Germany were by 1900 equal electric power capacities in alternating and direct current capacity installed; especially new and large power plants were mostly equipped with alternating current technology while single generators and smaller plants often still used direct current technology (Fischer et al., 1992). The connection of the surrounding industries to the electric power network in the first two decades of the 20th century drove centralization and the installation of larger power plants that were often even perceived positively[20].
The electrification of the outlying industries finally gave an incentive to build transmission infrastructure into the surroundings, and thus opportunity cost for connecting the adjacent households became smaller. Power companies offered fairly low prices and an—at that time—novel payment plan for installation of a power line into the house, as they expected higher gains from electricity sales later on (Nye, 1990). Additionally, it was the first time that light in the evening hours and nighttime was not the prime application of electricity, so that connecting more households offered better load balancing towards later hours of the day, when the industrial facilities were shut down and the traction was not used much (Nye, 1990). For usage in private homes—but not for industrial customers—the electricity was still for long transformed into direct current (Fischer et al., 1992).
This electrification of the industries, as further explained in the next section, at first led to only minor changes apart from the eliminated explosion hazards that gas light posed. Efficiency improvements were only observed starting around 1920, when factory layouts were changed and machines got separate electrical engines.
Both, direct as well as alternating current systems have to be levelled or balanced to allow proper functioning of the appliances. Commonly, appliances can handle a

[20]Civic pride even appreciated the higher smoke stacks erected with increasing power plants as they were interpreted as a symbol for progress and modernity. Often it was locally claimed to be the tallest in the world, as happened in Muncie, Indiana (Nye, 1990).

few percent difference of nominal power so that both, too much as well as too little power, should be avoided. Direct current systems were often levelled with batteries. Despite the rise of alternating current systems, in Germany 15 % of the power supply in 1905 came from batteries in which the electric energy was temporarily stored. Energetic advantages of this practice were only minor due to losses for energy conversion, but losses due to starting or stopping the power plant could be reduced (Fischer et al., 1992). In contrast, storage of energy in batteries is not easily possible anymore with alternating current. Instead, hydroelectric power sites took over the role of levelling the load curve: when there was a surplus of electric energy, the turbines are reversed and used to pump water back into the dammed reservoir; during a lack of electric energy, more water was allowed to fall This practice is still used today, although besides hydroelectric power plants, also pump-storage plants are installed to achieve higher levelling potential.

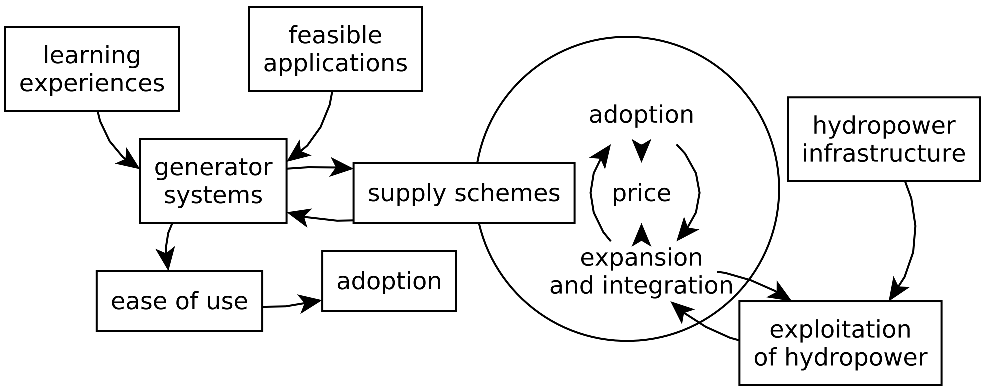

Figure 3.4: The dynamics of the network expansion.

Besides the organizational centralization of electric power networks, the integration of physical networks continued and regional electricity grids encompassing various operators of increasing size emerged (Fischer et al., 1992). A bigger size and more integration generally meant less need for reserve capacity, but also a higher shock resilience and stability. Furthermore, the management effort of balancing could be reduced which also lead to decreasing prices. And every decrease in price lead to higher usage which again facilitated the installation of more efficient and bigger plants decreasing prices again. This was a strong feedback loop driving the large-scale adoption of especially industrial electric power. Even in modern electric power networks, striving for better load management and less necessary reserve capacity can be observed as reasons for expanding grids.

3.3.3 Electricity in Business and Industry: Light, Heat and Motion

Not only were businesses and industries sought to be attracted by advertising claiming high availability of electric light and heat in the city (Nye, 1990), but also industries and businesses adopted those technologies for its own use. Electric light

started being used in the 1880s: just as steam power produced dirt and involved risks of explosion compared to water power, also any other non-electric source of light involved a flame and thus posed risks of explosion and emitted exhaust gases. In contrast to the possibility of gas leaking from pipelines or broken gas lamps, a broken light bulb did not pose any risk of explosion, as salesmen liked to demonstrate. Furthermore, fire insurance was dramatically lower for those industrial facilities and businesses that adopted electric light, exactly because of this relation (Nye, 1990). It is hence not surprising that flour or textile mills which were among the last to replace water power with steam steam power, had been among the first to replace gas light by electric light. Also merchants such as large retailers for clothes as well as department stores installed electric light from very early on: additional to the eliminated explosion risk, they preferred electric light not only because people were attracted to the electric light in shop windows and stores leading to more consumption, but also "because gas jets gave off smoke and highly acidic fumes that harmed fabrics, particularly when combined with the large amounts of water that burning gas produced as a by-product, dampening interiors and fogging the show windows" (Nye, 1990, p.5).
Public alarmboxes connected to firestations, as well as electrical alarms against fire and burglars, and even devices for monitoring the regular appearance of watchmen were often installed already in the late 1880s. A few years later, besides the often already existing telegraphs and electric lights, electric bells, as well as signalling systems for process management became commonly adopted in businesses and industry (Nye, 1990).

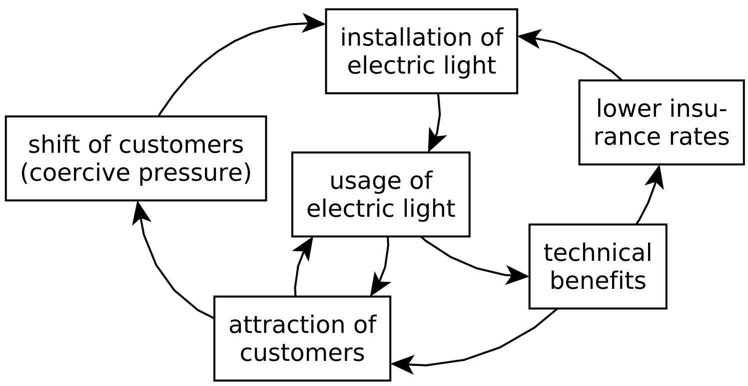

Figure 3.5: The dynamics of the electrification of businesses.

But apart from these smaller appliances, a general adoption of electricity for industries—besides those aforementioned sectors of electrochemistry and metallurgy—came much later although the pure availability of electricity at a factory already created incentives to make more use of it. Single factories already replaced their steam engines as early as the mid 1880s; but in the first applications the central steam engine was replaced by a central electric engine and the mechanical power distribution within the factory remained unchanged (Schobert, 2002; Grübler, 2003; Smil, 1994). Thus, efficiency improvements for factories remained low in these early years, even when one central engine was replaced by a few central engines (Grübler, 2003). According to Schobert (2002), the first fully-electrified factory, a cotton mill, existed by 1894, but still it took a few more years until the decentralization of engines took place and in turn could lead to not only more efficient factories by individual regulation and less distribution losses, but also could factories be built regardless of proximity to sources for water power, coal fields or infrastructure nodes.

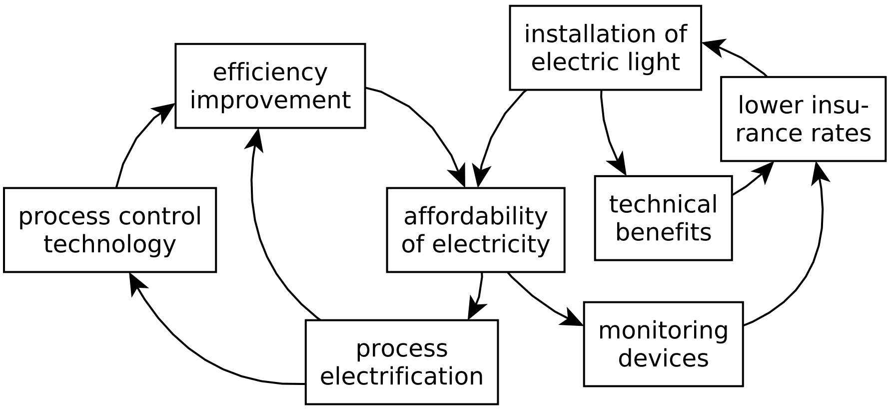

Figure 3.6: The dynamics of the electrification of industries.

Only in the first years of the 20th century, whole sectors became electrified; among others these were machine shops or glassware processing with processes like heating, electrolysis, polishing, blowing, moving, spinning, and many more (Nye, 1990). The advantage electricity over gas was that it could not only provide light and heat, but also could it drive many smaller or bigger motors, did not consume oxygen for heating, could link a serial installation of machines through moving belts, feeding devices or scanners. Furthermore it allowed to control, monitor and manage processes with appliances such as heat sensors, automatic shut-off devices, warning bells and many more (Nye, 1990). These all facilitated the development of modern factory production and allowed longer and more efficient operation of factories (Nye, 1990; Schobert, 2002). The increasing electrification in the early 1900s "eliminated both costly skilled labour, like glass blowing, and brute work, like carrying heavy loads" (Nye, 1990, p.15), leading towards high demand for semi-skilled workers with short learning periods. The development finally resulted in individually motorized production steps during the 1910s and 1920s, as seen in for example the famous mass production systems in the automobile industry, such as implemented by Ford (Hounshell, 1985). Grübler (2003) mentions that the subsequent decentralization led to doubling of the efficiency by the mentioned individual control of machines and improved factory layouts with regard to work flows instead of mechanical power flows.

3.3.4 Societal Perspectives on Electricity

Besides these technological trends, also social expectations and developments facilitated the electrification. Maybe most intriguing are the magical capabilities that people attributed to electricity because it could do things unimaginable only a generation ago. The public's first contact with electric light was probably in theatres, streets or lighthouses temporarily lit with electricity. But already telegraphy shaped the perception about electricity. What kind of force might it be that allows communication—via text and later verbally—over hundreds of kilometres in an instant? What kind of force could at the same time create a light that was neither flickering nor consuming oxygen? It is interesting to imagine how different the perception of steam power and electricity was at this time: although steam power sources had been widely introduced during the first half of the 19th century, it had always been perceived as a loud, dangerous, dirty, and crude technology, which intended to take jobs away. However, until the end of the century, though commonly accepted and widely spreasd as a power source and helping force, thi perception never changed completely. On the opposite side, electricity brought great pleasures and previously unimaginable achievements; it was silent, clean, and brought new opportunities to the people. It might have been a dangerous technology as well, but at least in the beginning the advantages and the fascination that electric lighting brought were overwhelming. With these perceptional preconceptions, there was nothing from a popular perspective that could hinder the general rise of electricity. For further reference, Nye (1990) wrote a very good and detailed account of the population's fascination towards electric light but also their discontent about certain technologies or practices.

3.3.4.1 The Attraction towards Electric Light

In particular, incandescent light became a prestigious object soon after its large scale introduction by Edison. Despite the economic benefits of using electricity compared to gas or oil for lighting, the high initial investment cost did not make it possible for the common man to install the generator system that Edison envisioned and started selling around 1880. They were sold all over the world to customers such as entertainment centres or luxurious hotels (Nye, 1990). As Nye (1990, p.32) writes, "The location of these early plants in central cultural, political, and economic institutions established incandescent lighting as an upper-class prerogative".

With early transmission technology it was impossible to transfer electricity over long distances. Instead, the maximum reach was a few hundred metres at maximum, necessitating a local and thus decentralized generation infrastructure that hence manifested privileges and classes (Nye, 1990). Together with the fascination for the electric light in general, and the incandescent light bulb in particular—it did not burn down, was not overly hot, did not consume oxygen, and did not emit smoke, while in contrast the arc light had to be adjusted regularly (Nye, 1990, p.2)—electric light became a magnet for attracting people. In the early 1880s, public demonstrations of electric light were covering all of the United States. Fostered by high media coverage as well as special trains, after those increasingly large events virtually any town or city that wanted to be modern or interesting had to install better and electric public light (Nye, 1990).

Besides the public light, also light in stores proved to be a big success. At the beginning they were only installed in larger department stores or warehouses, but soon whole commercial districts were lit by electric light; people were more attracted to electrically lit shop windows and stores, and thus electric light did not only help to reduce risks of fire, to reduce the fire insurance expenses in turn, and to avoid the smell, but also to attract the crowds (Nye, 1990). By the early 20th century, public electric light was a symbol for growth, progress, and cultural advancement. During that time, public lighting systems—until the mid 1910s still with electric arc lights, later increasingly with incandescent light bulbs—were not seldom financed by the local merchants as a response to declining popularity of their respective business district (Nye, 1990).

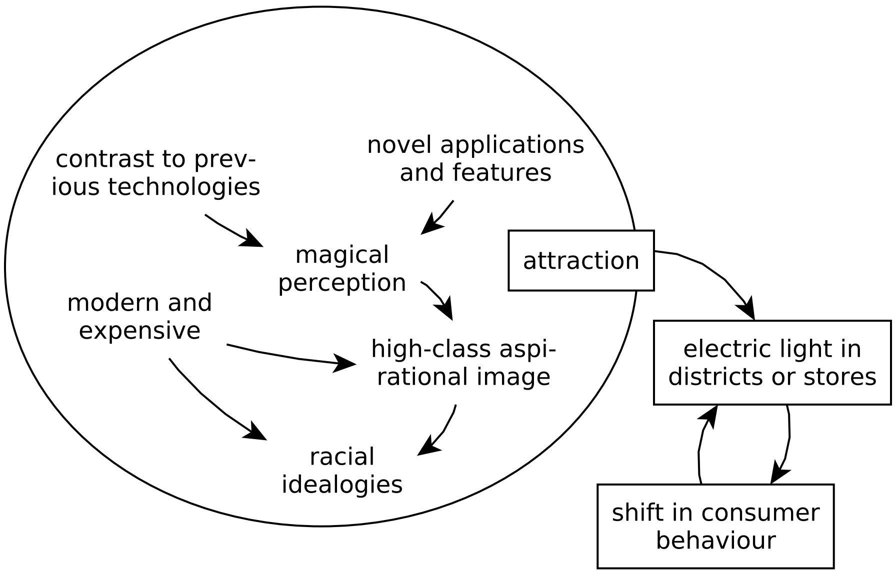

Figure 3.7: The attraction towards electric light and the dynamics of its adoption.

Because public lighting in general had advantages of increased security and wellbeing together with reduced crime rates, it was commonly known and applied in cities, electric light had many advantages over gas light in public spaces. Electric arc lights had an enormous brightness and were thus able to increase safety even more; for lighting the streets it was often already sufficient to install one arc light per crossroads (Nye, 1990). Also, electric light was easy to manage and to maintain, and it was not sensitive to weather conditions; in contrast, gas lights had to be turned on and lit individually, and often died when it was too rainy or too windy. Therefore electric lighting proved to be economically efficient as well, unless there was a cheap natural gas supply available locally (Nye, 1990); however, the commonplace corruption and mismanagement at the time often led to insufficient management or installation of power resources (Nye, 1990). In the beginning electric light could attract people and be a valuable tourist magnet, but quickly it became a sign of progress and a town without electric lighting would be seen as underdeveloped. To illustrate the effects of this perception: for example, the local businessmen of Muncie, Indiana, advertised the local benefits towards businesses and industries by pointing out the availability or even abundance of electric light and heat; they claimed that Muncie was “the best lighted and heated city in the country” and that “there is not a better city electric lighting plant in the state” (Nye, 1990, p.6).

3.3.4.2 Spectacular Lighting

Besides conventional lighting, the so called spectacular lighting always stimulated the minds of the people. There were various locations, events and developments that were outplaying each other by increasing the spectacle; if something was not brighter, not more colourful, not more animated, or not more exciting than something that had been seen before it could not gain more attention either. But if it gained attention it gained a lot. Following this tradition among others the famous light advertising of the New York’s Times Square emerged as will be elaborated later.

Other locations were the large expositions that had increasingly been a place for the presentation of new technology to the society during the second half of the 19th century, mainly because a novelty could be presented to a very large amount of people (Nye, 1990). Besides the fact that electric corporations were often advisers to the expositions, this public presentation of innovation caused the electrification of the US to largely coincide with the expositions. They drew a big contrast to the reality of the day by creating bright and fantastic visions about the society (Nye, 1990). Aided by special trains and organized round-trips, around one third of the US population was able to attend at least one of the fairs in the decades around the turn of the century, so they could bring home visions and ideas for their communities. Electricity served great for creating these visions, as Nye (1990, p.35) explains: “Organizers looked for elements of display at once refined, abstract, expensive, and as modern as possible, and electricity had all of these qualities. It was so abstract that it could be known only by its effects: light, heat, and power.”

The way and appearance in which electricity was displayed strongly coupled it to progress and superiority, so that soon it became part of racial theories and social Darwinist ideologies: darkness was seen as the primitive whereas progressiveness of a society was seen almost equal to the use of electricity (Nye, 1990).

Besides spectacular lighting at the expositions, whose amount often outweighed the total installed electric lighting capacity in any city of the country, also modern transportation systems such as electric trains, escalators, or moving sidewalks could be often first experienced at these world fairs. To keep visitors interested, every fair had to display more exciting and more interesting installations than before. Partly due to that also a new specialization away from engineering rather towards presentation and light installation emerged (Nye, 1990).

Originating from the spectacular lighting of fairs was also the practice of illuminating important places and landmarks. For example, in 1886 the Statue of Liberty got illuminated, creating a nice contrast to the darkness of the harbour. By the 1920s the Niagara Falls—after having been illuminated during the world fair in Buffalo in 1901—permanently held advertised light shows, as well, making it a regional and national tourist magnet not only during the day but now also at night.

In New York and other large cities, commercial light installations of all sorts were a commonplace; this was mainly advertising serving to gain the attention of the visitors, and as a whole the installations were creating a gloomy, bright atmosphere that attracted shopping crowds (Nye, 1990). Though the first light advertising was used in 1883 in New York to advertise a fair, the spread of electric advertising only came in the next decade. Light advertising soon proved perfect to attract the masses, to transmit the advertised claim more thoroughly and to increase the general attraction of a whole district (Nye, 1990). The vicious circle of the ever increasing spectacle that already occurred at world fairs also captured this industry; then, in the early 1900s illuminating engineering became a profession and the first dynamic advertising appeared. Soon after, some kind of large video screen consisting out of thousands of light bulbs that could be booked to show short clips (Nye, 1990). These new kinds of dynamic advertising soon became a topic to talk about and people even intentionally passed them to be up to date.

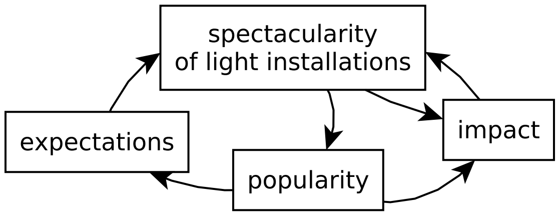

Figure 3.8: The dynamics of the spectacularity of light installations.

During the first two decades of the 20th century, the word on the so called White Way, the highly illuminated commercial centre on the Broadway in New York, spread. At first businessmen who encountered decreasing popularity of their business district wanted to copy this successful model of attraction; they tried to boost their commercial success by installing public lighting—not so much advertising as in the role model. In the 1910s also more and more communities took over the investment into public lighting infrastructure for business areas. From a means to attract people to expositions, light became an important part of commerce and the cityscape. As already noted earlier, the electrification denoted progressiveness, and thus an electrified city wanted to display some kind of cultural advancement, modernity and progress (Nye, 1990).

3.3.4.3 Electric Traction: Mobility for the Classes

As explained earlier, the economic considerations of load management for traction companies brought quite some novelties and excitation into the world. This section will elaborate on the social effects of cheap and fast traction systems.
While steam powered traction was a mature technology for regional connections and in a few cities, electric traction was still a novelty in the early 1890s. Therefore many towns such as Muncie, Indiana, first tried to implement a steam powered system on a street level. However, in strong contrast to New York where steam powered trains were running on elevated tracks, on the street level steam power seemed to be less accepted (Nye, 1990). Nye (1990, p.9) quotes the *Muncie Daily News* from 1892 to give an impression of the perception back in the day: “The good citizens of Muncie are tired of seeing them [the steam powered streetcars] bowl through the public thoroughfares with their smoke, rattle and cinders, scaring horses and

causing havoc generally". So less than one year after its introduction the steam-powered streetcar was replaced by the local businessmen who jointly implemented an electric streetcar system, not only quiet and clean but also able to accelerate faster and to stop in more convenient locations (Nye, 1990). The established streetcar systems led to rapid suburbanization all over the United States, and not seldom did the directors of streetcar companies make good money by land speculation as land prices skyrocketed everywhere where a tram stop was built (Nye, 1990).
Therefore, the introduction of urban traction allowed more segregation and specialization to take place in cities: business, shopping and entertainment districts emerged in the city centre, while factory districts and suburbs shared the periphery (Nye, 1990). This on the one hand increased the variety of stores and gave place to big department stores, but on the other hand this shifted the focus from the local neighbourhood towards a life more spread out over the city. Urban entertainment and amusement centres often emerged at the crossroads of various streetcar lines; they could eventually buy electricity from the traction company or a local, private utility and they attracted many visitors that could easily reach these districts due to their central location.
The population structure changed, too: the growing middle class largely moved away from the city centre, built bigger houses in the emerging suburbs and commuted to work every day by streetcar (Nye, 1990). The lower classes in contrast remained close to the industries since often those were not connected to the public transport system; hence they continued walking but in turn used public transportation to reach the commercial districts in the weekends (Nye, 1990).

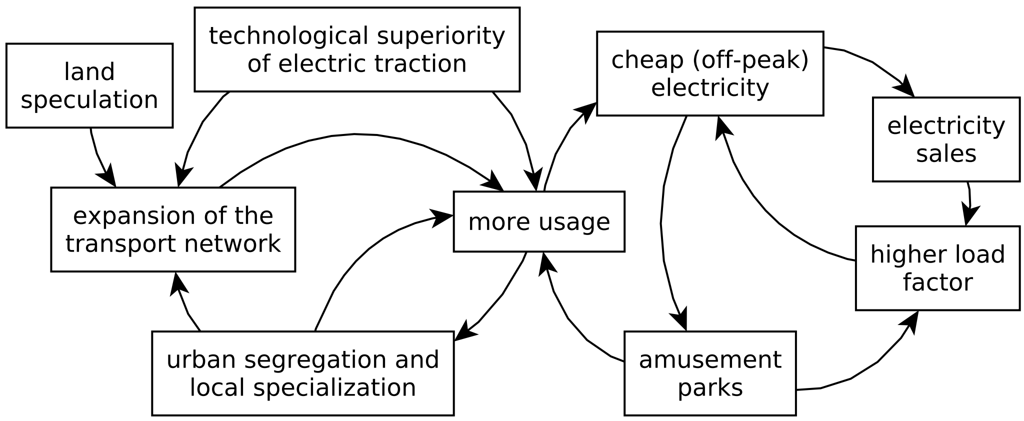

Figure 3.9: The dynamics of electric traction.

Not only did the urban population use the trolley ride into the countryside as a spectacle and as recreation, especially during the hot summer months in the open trolley cars, but very soon traction companies built and ran amusement parks at the final stop of a line (Nye, 1990). As explained earlier, this development was highly motivated by increasing the load factor of the electrical generators. At that time, amusement parks emerged all across the country, and during those hours when amusement parks ran on full load—in the nighttime, on weekends, and during holidays—the general demand for traction was lower because no one commuted to work. Not only did the amusement parks contribute to motivate people to use traction on the weekends, but also were all the installations—rides, spectacular lighting, theatres, and many more—highly profitable means for converting electric power into money (Nye, 1990). It was a means to get out of the city and into a fun, cheerful and colourful place where the problems of an industrial society could be forgotten, it was "serving as a feast of fools for an urban industrial society where the patron momentarily escaped into a magical world" (Nye, 1990, p.12).

3.3.4.4 Electrification of the Common Households: Changing Lifes

Only very rich households could afford their own electric lighting system in the late 19th century, and only those in the city centre could be connected to the small private electric power networks. But after the electricity consumption in the industries took up in the first decades of the 20th century these were connected to the central power plants. Since the electricity grid passed the adjacent neighbourhoods on the way to the often outlying factories, power plants soon offered consumers to install a connection to the electric grid (Nye, 1990). Just as other developments, this was also driven by load considerations: earlier, the main load came from the demand of stores and businesses in the city centre, and they needed electricity mostly for lighting. Hence, any network expansion would have necessitated an expansion of the generating facilities, too. However, with the centralization of power providers and the connection of the industries, the major load started to shift from the evening hours with intensive lighting towards the daytime when there was a high demand of electric power for powering machines and other processes (Nye, 1990). Therefore any increase of consumption in the evening hours could improve the load factor again. Starting in the 1910s, companies offered very cheap installation of connections, hoping to get costs back by electricity charges. Financing was done by at that time novel payment plans that spread the total cost of ten dollars over ten months; with an average daily working-class wage of $ 2.50, this was affordable to basically everyone (Nye, 1990).

Before around 1910, common private connections to the electric grid had a physical limit of 100 W, so that the connection fused when this limit was exceeded for more than a few seconds. 100 W were nonetheless sufficient for one or two light bulbs—often paid not in terms of actually consumed electricity but on a "per lamp and week" basis—, but because around that time more different appliances started to be sold, this physical limit was often not sufficient anymore (Nye, 1990). Theoretically, many highly-consuming devices were constructed to need exactly 100 W to cope with this limit, but consumers complained that lighting lost its intensity or the connection fused because of too high power consumption. Besides the consumer complaint and the upcoming new appliances, the utilities also wanted to make more money, and as a result they started offering metered service in private households starting around 1905 (Nye, 1990). For this, the connection to the grid had to be renewed, a meter had to be installed, and the consumption had to be read off in regular intervals.

While the market for metered service grew within the next five to ten years, it was quickly accompanied by door-to-door sales of appliances which were also organized by the utility; with these sales they tried to increase the use of electricity in the household. Although the campaigns were sometimes not profitable theirselves, the revenues from increasing consumption of electric power quickly made up for this loss (Nye, 1990). After the market grew bigger, new appliances were in the centre of attention every year: early on, the focus laid on smaller items such as irons, toasters or vacuum cleaners, while one to two decades later the focus shifted towards larger items such as refrigerators or water heaters because the market for smaller items was almost saturated. The increasing sales led to a point in the 1930s when domestic demand exceeded the commercial consumption of electricity (Nye, 1990). Besides these door-to-door sales, during the 1920s there was an increasing number of road shows or public demonstrations of new appliances—similar to those that made electric light popular and well known over 40 years before—at fairs, model homes, or in downtown theatres (Nye, 1990).

Although electric versions of items such as fans, cookers, or irons were invented already in the last decades of the 19th century, they could not take up higher market shares until domestic households were largely electrified. Especially after World War I, sales of electric appliances increased drastically and many small companies or entrepreneurs felt encouraged to join the competition because, as Nye (1990, p.18) writes, "anyone could make a device that plugged into the network". This largely stood in contrast to gas for lighting, telephone, or telegraph, which all had a large impact but could not create opportunity for so many additional appliances or machines. While the market for smaller appliances was largely occupied by the smaller actors, the bigger actors such as the large electric corporations focused on the development and sales of the larger appliances such as laundry machines or water heaters (Nye, 1990).

Many practical innovations and their spread in the early 20th century were facilitated by the omnipresent access to electric power, replacing more cumbersome non-electric items or processes, or bringing whole new realms of application. Among these numerous new technologies, maybe the radio is the most valuable and relevant; it was originally intended for point-to-point communication by the military but amateurs started off with sending some programmes, subsequently creating a demand for it (Nye, 1990). This ultimately led to the first commercial and later also public radio stations in the early 1920s. The radio proved to be a genuinely new experience, attracted attention and served as a monodirectional communication medium not only for national pop culture or news, but also for advertising and corporate interests (Nye, 1990). Other interesting appliances invented in that time are for example the refrigerator, electric drills and sanders, and also the electric corn popper. However not all of the inventions proved to be an instant success; the electric refrigerator, for example, became only common in the middle of the 20th century because the previously used system of large-scale ice manufacturing and distribution was fairly good in the United States (Nye, 1990).

The electrification of the household also drastically changed the way society worked and interacted. Electric light was probably the first application that could show an effect of electrification onto the general public: besides the aforementioned attraction towards electric light in stores and the increased security in the public, the equipping of schools with electric lighting and therefore the enhancement of the vi-

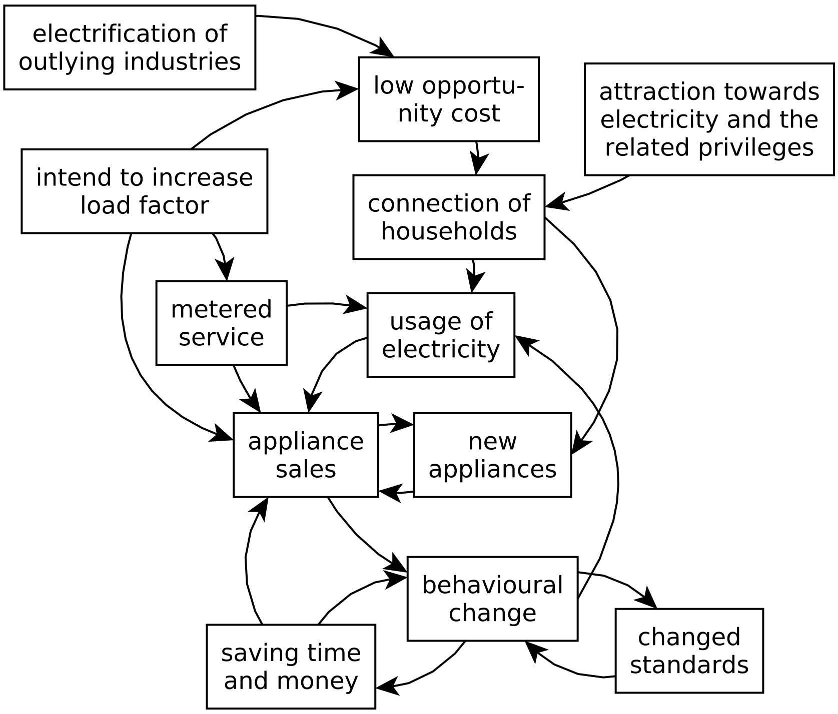

Figure 3.10: The dynamics of adoption of electricity in households.

sual circumstances encouraged reading (Nye, 1990). Also at home, children could now read more since they were often allowed to use electric light, while due to the involved dangers they were mostly forbidden to use gas lighting. Besides other reasons, this was probably one cause why libraries could largely increase their impact and loaned a multiple of what they loaned before the turn of the century (Nye, 1990).

Another huge impact can be attributed to the spread of water heaters using gas or electricity: while earlier, heating cold water was highly time consuming and thus people brought their clothes to commercial laundries and washed theirselves in public bath houses, with the introduction of water heaters, laundering, cleaning the dishes, or bathing became much easier (Nye, 1990). This increased adoption of these practices at home, changed their frequency and subsequently altered the standards for cleanliness; it became simply not sufficient anymore to bath and launder once a week (Nye, 1990).

Additionally, the rise of communication devices such as telegraph, telephone or radio supported perceived progressiveness and cultural superiority that was already triggered by the electric light. At the same time, feelings of separateness became weaker; as Nye (1990, pp.18-19) puts it: "Everywhere can be wired to everywhere else. New electrical terms that permeated common speech likewise emphasized connectedness." But in contrast to business and industry, where telecommunication had a huge impact, the radio rapidly and substantially changed private life, interaction and behaviour. — Basically, the new technologies largely made certain tasks easier, more affordable or faster. This left more time and money for further consumption.

3.3.5 Electrification of the Countryside

Already in the 1870s small wind mills with buffer batteries were installed in farms in the United States and Europe to pump water for drainage and irrigation; however due to power instabilities, until 1900 many wind power systems were replaced by hydropower where this was applicable[21] (Strandh, 1979), and many more systems were installed later on (Nye, 1990). Also electric agricultural machines were developed already in the 1880s, for example machines for plowing, threshing, hacking, hatching eggs, and even special lights for faster plant growth were available (Strandh, 1979; Nye, 1990). But usually they needed too much power to be used with the small electric generators that could be powered by locally available wind or water. While Central European governments often publicly managed the electrification so that access and usage of electric power in the agricultural sector was much more advanced in the early decades of the 19th century, in the United States private enterprises were the main driving forces of electrification[22] and they did not see enough profit in electrifying the countryside (Nye, 1990).

Although many farmers—until around 1920 they formed the majority of the American population—wanted electricity, the increasing urbanization made it unappealing for utilities to invest into the electrification of the countryside, so that the aforementioned electrification of settlements along the electrified interurban railway tracks remained the only source of electricity for long. For the urban public, electricity was furthermore seen as a disturbance for the natural cycles of agriculture and the harmony between farmer and nature; however, rural schools or households could neither enjoy the advantages their urban counterparts had (Nye, 1990). The electrification would have highly increased productivity and efficiency of the farm, but the demand that farms posed was—maybe with exception of electric pumps—unstable and highly fluctuating with the time of the day (Nye, 1990). In 1910 Theodore Roosevelt, then president of the United States, called for "cooperative action among farmers, to put them on a level with the organized interests with which they do business" (as quoted in Nye, 1990, p.288), but not much happened since any shared interest could not outweigh profitability of the commercially-acting utilities. Towards the end of the 1910s a few farms installed off-grid electric generators, but by the end of the 1920s around 90 % of American farms were still without access to the electric grid (Nye, 1990).

Except for some well-meant but badly-appreciated deals with which consumers were offered grid access when they agreed to use so much electricity that the costs for electrification were made up for within a few years, there was basically no improvement in electrification and a government intervention seemed to the only suitable

[21] Only in regions completely unsuited for water power, the wind remained an important force. There were only a few countries that had to rely on wind power in large parts of the countryside. Denmark is one of them, so that the government, for example, funded research and development of wind power systems already in 1894. Although not the first in the world to construct them, already by 1957 they could deploy 200kW systems that were largely adopted (Strandh, 1979). Their long experience and the suited conditions made and still makes them an important location for wind power research and development, which internationally only could gain attention again after the oil crisis in the 1970s (Strandh, 1979).

[22] For a detailed account and comparison of the different governance approaches at the example of Berlin, London and New York, see Hughes (1983).

option to solve the issues (Nye, 1990). Thus, in the 1930s the national government finally acted and formed the regionally-operating Tennessee Valley Authority (TVA) in 1933 as well as the Rural Electrification Administration (REA) in 1935 which was working rather decentralized. While the TVA's very controversial purpose was to dam the Tennessee river in regular intervals and bring the gained hydroelectric power into the countryside—including all the administrative, regulatory and technical problems—, the REA's purpose was solely to facilitate building transmission lines to farms (Nye, 1990). It basically "loaned funds to local cooperatives that served areas overlooked by private power companies" (Nye, 1990, p.23); these funds were used to install transmission lines and later also assisted farm equipment sales when travelling appliance shows or local financing programmes for equipment were initiated (Nye, 1990).

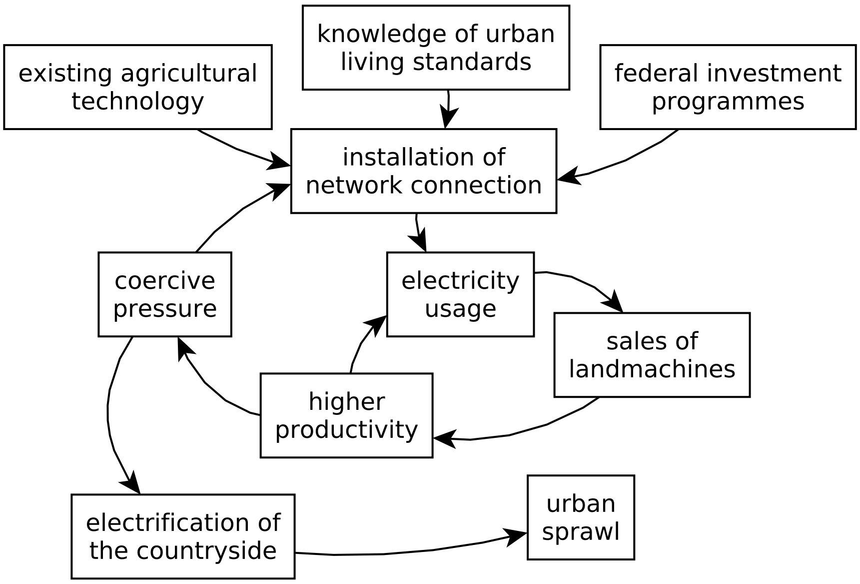

Figure 3.11: The dynamics of the electrification of the countryside.

Effects of these investment programmes were immediate, and electricity could take over lots of the heavy work on a farm. As a consequence, rural working conditions became fairly similar to those in urban areas, and the electrification of the countryside together with the rise of the automobile facilitated people moving back to the countryside (Nye, 1990) and probably urban sprawl. However, in the early 1940s the war made farms prosper and earn high profits. These ultimately allowed the large majority of farmers to invest into a connection to the electric power grid and to obtain valuable electric agricultural machinery. Unfortunately, because of the war, skilled workers were mostly unavailable at the time, and electrification of the remaining farms could only be finished in the postwar period. Besides the increased quality of the farm life this also brought a revolution in farm productivity all over the United States. However, the cooperatives that built and financed the electric system ultimately suffered from their own success: as farm sizes increased drastically with the efficiency gains brought, among others, by electricity, the cooperatives often lost their spirit and local entanglement (Nye, 1990).

3.3.6 The Generative Entrenchment of Electricity

In the data presented many scaffolds can be seen: these are learning processes and interactions that ultimately led to the entrenchment of electricity. This section will summarize the results, set the dynamics into a chronological context and identify the overarching self-reinforcing, *generative* dynamics of the entrenchment process. At the end of the section, Table 3.2 gives a brief overview of the main encountered feedback interactions; Table 3.1 displays a timeline over the most important developments related to the electrification.

Table 3.1: Timeline of the Electrification.

1800	discovery of electric current with the Voltaic pile
1837	first commercial telegraphy system
1844	first productive usage of electric light
1866	invention of the electromagnetic generator
1879	groundbreaking improvements for electric arc lights and light bulbs
1880	first electric power systems
1882	first power supply schemes
1880s	adoption of electric light in stores and the public
1889	first AC power plant
1890s	introduction of electric traction leading to urban sprawl
1900s–1920s	electrification of the industries
1910s–1930s	electrification of urban households
1930s	domestic demand exceeds industrial demand
1935–1950s	government-supported electrification of the countryside

3.3.6.1 Before the Electrification: Learning Processes

The learning processes involved in the pathway towards the general electrification of the society are diverse and of major importance (see also Figure 3.3).
As mentioned, there were three major pathways of technology, where telegraphy and electrochemistry shaped learning of the technological context, and the third one was the development of electric light itself, which was the first widely-spread appliance in an early-electrified society.
The idea for telegraphs existed already for a while although the technology needed major improvement until commercial feasibility was reached. The novel way of communication it provided—instantaneous and over long distances—opened up a large market demand for this technology. Especially the necessity for point-to-point connections led to an even higher demand for wiring and assisting technology. This large market and the money involved led to a highly competitive field providing the main learning outcomes for electric technology: (i) tools, appliances, and wiring; (ii) manufacturing technology; (iii) personal knowledge and skill development for electrical engineers and inventors; (iv) formation of professional networks and societies. All of these directly facilitated development of further important technology such as the electromagnetic generator and made large-scale electric systems generally feasible.
Secondly, electrochemistry provided a genuinely new field of application, a new and unique functionality for the application of electricity. In contrast to electric lighting which was competing with other technologies, electrochemistry developed in a non-competitive environment in which learning processes were triggered, as most of the achievements of electrochemisty, were novel and unique and did not compete with existing technology. Especially the necessity for large power output, which did not exist to this extent for telegraphy, drove the development of dynamos and generators, whose development was largely facilitated by the actors and knowledge involved in development of telegraph systems.
Lastly, there was the development of electric light. Since it was in a competitive relationship to existing technology such as gas and oil light, high initial costs and short durability were the most important factors why these systems were not adopted quickly. Only where the special characteristics of electric light could add an extra benefit so that a new development state could be reached, the adoption was justified; therefore it was applied seldom, but effectively. At first, applications were theatres, and lighthouses, while later applications at harbours or railway terminals were added; in all of these locations, the difference in functionality compared with conventional systems brought the reasons for early adoption. Together with telegraphy—which already made large scale electric systems feasible—the scarce but effective application of electric light created an image of electricity as a very useful technology, that gained a superior and magical notion as it allowed applications or usages that had never existed before. This perception gets an even higher importance when being put in contrast to other contemporary developments, such as the steam engine, which was loud, taking jobs away and only did things that already humans or water power could do.
Generally, the early developments set the stage for the spread of electric technology starting in the early 1880s. Many important inventions for applications were made, which can be seen as the fundamental scaffold for the appearance of new functionali-

ties that entrenched the electricity system. Early learning experiences could be made in the special cases, when electricity provided a unique developmental function, or where the technical features were clearly superior to then conventional technologies.

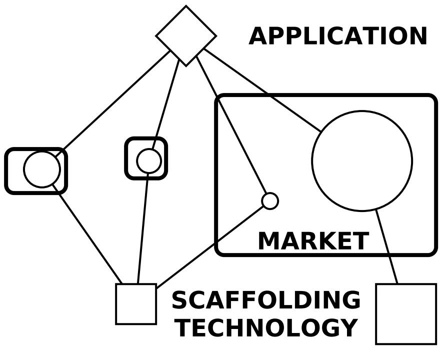

Figure 3.12: The diversity of competitive or unique application markets before the introduction of electric power systems.

3.3.6.2 Early Electrification: Small-Scale Installations

With the contribution of those engineers who saw the need for electric power systems, such as Edison, which required only little knowledge of electric technology, the electrification started. These were made possible by the learning experiences in generator and transmission technology, but also by higher attractiveness of electric light installations, which resulted from improved electric arc lights and light bulbs. Shortly after generator systems for single buildings appeared, a new business model utilizing the large economies of scale from network expansion was introduced: here, the application of electricity was split from the physical and administrative management of the power network, and the application could be isolated from the rest of the system. Because electric light had a huge impact on consumer behaviour as it was attractive, it also created attraction via the perception of superiority and it promised increased profits. Therefore the convenient solution of simply buying electric power instead of maintaining a whole electric system was greatly appreciated. Additionally, these new systems allowed for bigger and therefore more efficient generators, for a more diverse load structure, and cheap expansion for higher reach; these, all together, led to decreasing electricity prices. This pattern of expansion, adoption, and price reduction is visible throughout the history of electric power networks. At any time, an expansion of networks meant an increasing conservation because more profit could be made with the networks, more customers would eventually prevent failure of the system, and the overall systemic importance was increasing. Another important factor for network expansion, though not quite relevant back then, is risk reduction which comes form merging different grids and therefore creating a parallel structure. In this process, scaffolding by a single, specific plant are replaced by scaffolding interactions towards a multitude of technically equivalent and mutually replaceable plants.

While the first civil customers of generator systems around 1880 were expensive hotels, public institutions and wealthy civilians, who all wanted to foster their progressive, modern and exciting image, electric light was also used in business and industry. Here, from early on, especially those sites that were dealing with explosive goods, such as fabrics or flour, were inclined to make the switch, as electric light did not bear any explosion hazard. Furthermore, the insurance companies saw a benefit, so that insurance rates for places lit by electricity were cheaper than those lit by gas, while in most cases energy costs were lower than when using gas lighting, as well.
For businesses the usage of electric lighting bore the additional advantage that negative side effects of gas light, such as fumes, could be avoided. But this was probably only of minor importance in comparison to the consumers' attraction to electric light. This attraction led towards more adoption of light by the already electrified businesses, and additionally this also marked a shift in consumer preferences, so that businesses not lit by electric light might have been forced via mechanisms of coercive pressure to install it as well. In a way, this increasing usage of electric light by coercion can be seen as the first important increase in adoption of electricity, as the vast amount of different electric applications did not yet reach higher volumes. Furthermore, many of the industries and institutions had their own generator systems while businesses often relied on private supply schemes which were especially feasible in areas with many potential consumers, such as central business districts. Here, the technical context as slightly different allowances and side effects is of special importance for certain businesses as the main facilitator for early adoption and diffusion.
Also within the 1880s, the availability of electricity led to inventions of small devices such as fire alarms or burglar alarms which again might have reduced insurance rates or brought other benefits of financial or technical nature. These were probably only invented because the availability of electricity was assured by the usage of electric light, and therefore a novel functionality could build up on this. Although these devices were no heavy consumers of electricity, they provided a new and important function that could not be fulfilled with artifacts before, and therefore were strongly entrenched by their functional benefit and the developmental purpose they fulfilled.

3.3.6.3 Diversification of Systems: Chaotic Times

During the late 1880s and early 1890s, in many medium-sized towns a threefold structure of electric power systems emerged: a private system selling electricity to businesses in the centre, a public system for powering electric street lights, and a private system to drive the streetcars. In addition to this, there were many smaller generator installations for single houses or blocks; in larger cities probably many other systems existed in parallel, since the reach of an electric power network was not yet very big. Since no standards existed, each of these systems had different specifications, and this state remained for a few more decades before standardization and conservation ultimately triggered the unification of grids.
With the rise of traction systems, electric power acquired, after the electric light, the second important function in society which can be seen as a new generative subsystem: electric mobility. Although passenger transport with steam technology

would have been possible, electric traction appeared to be more feasible in most urban applications: compared to horsewagons they had a much higher reach and were much faster, compared to steam-powered traction, they were silent, clean and could accelerate much quicker. Because subsequently the urban segregation increased and the specialization of neighbourhoods and thus led to generally more usage of electric traction, this novel application of electric power quickly became crucial for the functioning of society. The ongoing expansion of streetcar networks only encountered its limits when the population density in the newly connected districts became too low to still provide economically viable mass transportation. Surprisingly, although it seemed highly entrenched, the electric traction system still disappeared later on and got replaced by hydrocarbon-based transport solutions on rubber wheels, buses and cars, which required much lower infrastructure investments in the dispersed suburbs. Nonetheless, electric traction can be seen as one of the clearest examples for the vicious circle of generative entrenchment (see again Figure 2.1).
Electric traction systems were inherently generative in a way that they not only entrenched the necessity of electricity in society, but also increased their own electric consumption by traction and other businesses. Main incentive for this was the low opportunity cost of generating off-peak electricity, which could be provided basically for only the fuel investment cost. Hence, two systems developed: at first, especially interurban railway companies sold electricity to communities adjacent to the tracks, which generated profits that ultimately exceeded the profits from traction. Secondly, traction companies constructed amusement parks, which not only transformed cheap electricity into valuable money but also increased usage of the transport system itself. Both systems increased the load factor of the system, making electricity even cheaper, and the system, because of its profit, more worthwhile to preserve for the operators. However, in contrast to the transport system itself, the provision of electricity to small communities and the existence of amusement parks was no inherent systemic necessity; instead, these were purely conserved because of economic profits.

3.3.6.4 The New Century: Expansion and Demands

By the turn of the century, hydropower and alternating current technology had provided important learning experiences for long-distance power transmission in a system of mutual facilitation. This development was mostly scaffolded by the existing large direct-drive hydropower infrastructure, especially dams, that became less important with the success of steam power: these systems were easy to exploit since the biggest infrastructural investments as well as the knowledge about seasonal patterns and exploitation of power were basically existing, and only the transmission to distant destinations had demanded further innovations. These innovations were adopted to an increasing degree in power transmissions systems which allowed larger network expansion.
At that time, the institutional structure with a multitude of different network operators tended to cease as the amount of actors decreased when systems became more centralized. In addition, within towns, the demand for more public and spectacular lighting grew. The story is similar to the story of light in businesses: the people's attraction towards electric light led to initial adoption by some individual districts,

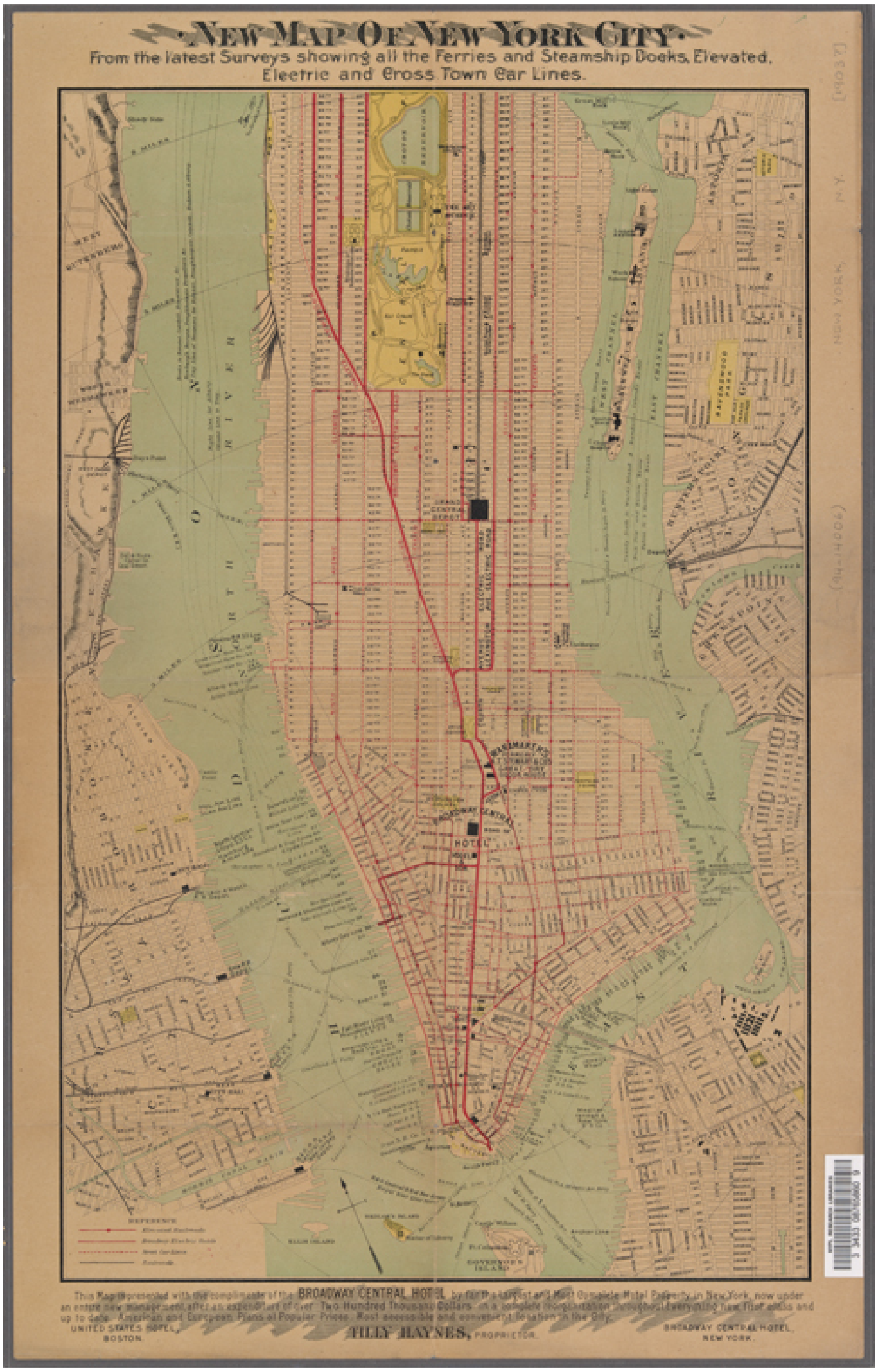

Figure 3.13: Map of New York's public transport system in 1903. (The New York Public Library, first published 1903).

towns or stores. Since this proved to be a successful attraction for the crowds—for tourism to places with public electric lighting in the beginning, then for stores that could increase their sales, for business areas which could attract more businesses, or commercial districts that could attract more customers—consumer behaviour changed respectively and other towns, districts or stores had to follow to not lose their market position.
By then, electric light had also brought some kind of magical perception of electricity; the fairs had displayed electricity as a modern and expensive good which not only led to the perception of electric light as an upper-class privilege but also to racial or social-Darwinist ideologies, so that any place that might not have electric lighting yet might be seen as inferior and backward. Therefore, there was also some kind of expectation towards communities or business districts to provide proper lighting; especially since any town additionally wanted to mimic the great "White Ways" of New York or Chicago and be associated with all those ideas people had about these great cities. Lastly, light advertising broke ground: not only was this attracting masses, but especially in bigger cities, a novel advertising campaign could be the discussion topic of thousands of people, and thus had a relevant impact for marketing of products or brands[23].

3.3.6.5 Completion of Urban Electrification: Ultimate Dependency

Due to improved technology and expanding networks, many factories became electrified in the first decades of the 20th century and therefore added new functionality to the electric network; due to the introduction of the streetcar these factories had often moved to the outskirts of the cities, so that more powerful transmission was necessary now. Earlier availability of electric light had brought further incentives to generally electrify certain processes in the production. This also opened up a demand for process control technology, devices for monitoring or steering the processes easily. Both, the electrification of processes and their control, were able to increase efficiency of the business on the short run—when different input energy sources and thus the respective management effort were merged—and on the long run—when restructuring led to improvements in manufacturing efficiency as well. Both processes also made electricity more affordable as upon higher adoption and load, unit prices become cheaper and thus more attractive to use.
The following electrification of American households probably had the highest impact among all the different processes during the electrification, as private consumption of electricity soon exceeded commercial demand for electricity. This was made possible by the electrification of the outlying industries, because in consequence of this the opportunity cost of the households located in between had decreased a lot. The utility hoped to achieve higher sales of electricity in general, and a higher load factor in particular, when the consumers got electricity access, or later metered service, so that electricity demand especially in the evening and the nighttime was increased. The consumers, in turn, were simply happy to be able to finally enjoy the

[23]Actually, the concept and benefit of branding or brand advertising, in contrast to product advertising, was just introduced during the turn of the century, when more and more light advertising was created.

privileges and affordances electricity brought; by the time they became electrified, these were many more than simply electric light, but also many other appliances.
There were quite some powerful dynamics involved, that drove the electricity consumption higher and higher during the following years. While at first many tasks simply became electrified, soon entrepreneurs and larger corporations developed new appliances, because the simple availability of electricity access in houses made this a profitable business. Consumers not only actively bought appliances, utilities also actively sold appliances. These added new functionality to the overall power system and also to the individual's importance of electricity.
All devices could foster behavioural change by the availability of these devices, which are in a way increasing the importance of the previously achieved developmental functions. This change can be identified on three levels: (i) the new behaviour the appliance brought often led to more electricity consumption, such as listening to the radio, or cooking with electricity instead of with wood or coal; (ii) with the new affordances of the bought appliances, standards, such as for hygiene, changed across the society so that people generally adopted new or changed practices; (iii) often, the new behaviour led to savings of time and or money, so that on the one hand, more appliances could be afforded, and, on the other hand, more time could be spent on further consumption.
With these developments that fostered rapid and creative innovation using electric power—not only in private households but also in the industry—, for the first time after electric light and electric traction, the use-phase of products necessitated electricity, and the range of products was expanding. This allowed the system to become ultimately entrenched since many industrial and private appliances, as well as the previously existing light and traction systems, now entrenched the basic functionality of the overall societal system: movement patterns, individual behaviour, societal standards, working life, shopping activities. Although theoretically the one or the other realm could be viable without electricity, the overall conglomerate of electricity-consuming appliances in production, distribution and usage, entrenched the electric power system to an irreversible extent.
However, still there were many different system specifications existing, that remained for a few more decades until they came fully unified. Especially remaining small generators in all parts of society added up to also a variety of different specifications that products had to be adjusted to. But with the increase of appliance and electricity markets, the diversity vanished.

3.3.6.6 Dispersion of Networks: Finally, Electricity for Everyone

As the last part of the American society to become electrified, the electrification of the American countryside was highly beneficial for the general productivity of agricultural output, especially coupled with the green revolution in post-war years. These network expansions involved a lot of standardization and substantial integration of networks towards a rather unified electric power system. There were two important pull-mechanisms in this process, the already existing and established electrical agricultural technology in Europe, as well as the high difference of urban and rural living conditions. However, investment costs were too high for individual farmers, so that eventually only a push-programme by governmental investment led towards a widespread connection of farms to the regional electricity grids. The installation of network connections led to some initial electricity usage, fostered the sales of electric landmachines and agricultural appliances and ultimately not only led to the possibility to enjoy the pleasures of electricity in rural living circumstances, but also to higher productivity. These higher productivity resulted in more adoption of agricultural machinery because they became affordable. Finally, the electrification led to a general pressure towards productivity improvements that was quickly electrifying the whole countryside.

Table 3.2: Identified feedback loops leading to entrenchment during the Electrification. Besides the realm and a detailed description, also approximate beginning and end of this development are listed.

case-study	description	time
electric traction	existence of streetcars and the related network extensions lead to segregation, specialization and suburbanization, all leading to more usage	1890s–1910s
electric traction	cheap electricity during off-peak hours of electric traction is sold to communities adjacent to the tracks, who often applied it for lighting, but later used it generally	1890s–1910s
electric traction	cheap electricity during off-peak hours is used to operate amusement parks which increase load factor and reduce electricity cost	1890s–1910s
electric traction	design of amusement parks leads to more trolley rides during off-peak hours, and thus to a greater profits and better load factor levelling	1890s–1910s
networks	power supply systems are improved by the demands from supply schemes, while in turn supply schemes become more common because of the advances in technology	1880s–now
networks	the existence of hydropower developments from the pre-electric era fosters the development of long-distance transmission technology which leads to network integration and also to more exploitation of hydropower resources	1880s–now
networks	via the mechanisms of economies of scale, network expansion reduces production prices by higher demand, as well as expansion and conservation which decrease management effort	1880s–now
business & industry	adoption of electric light has technical benefits (leading to systemic conservation of electricity)	1870s–1920s

Continued on next page

Table 3.2 – *Continued from previous page*

case-study	**description**	**time**
business & industry	electric light has technical benefits which were displayed by lower insurance cost and thus increased electric lighting (that lead to systemic conservation of electricity)	1870s–1920s
business & industry	installation of light and the coinciding availability of electricity led to quite a few inventions such as fire or burglar alarms which increased the conservation and necessity of electricity	1880s–now
business & industry	the alarm systems invented and introduced because of electric light could probably also lower the insurance cost leading to economic incentives to adopt them in other industries	1880s–now
business	once a business had electric light it noticed that it lead to some attraction of consumers, leading to more adoption	1870s–1900s
industries	the existence of electric technology makes it easier and more affordable to use electricity for more processes to have a smaller variety of input streams; thus early usage led to more conservation later on, while real efficiency gains in the production come still later	1900s–1930s
industries	availability of electricity and electric input sources make management and steering of the technology by electric control technology much more affordable and thus lead to further efficiency improvements	1900s–now
light	existence of electric light in one business district, store or other establishment could lead to a drastic shift in consumer behaviour towards this place, so that competing establishments needed to equal or exceed the others	1880s–1920s
light	the initial excitation and astonishment when people saw electric light soon led to spectacular installations which however triggered expectations of the population so that ever bigger and better spectacle; this approval of expectations led to higher expectations in turn	1880s–now

Continued on next page

Table 3.2 – *Continued from previous page*

case-study	description	time
light	the popularity the spectacle had also had a certain impact on society as good light advertising was always a good discussion topic; this impact triggered higher usage of spectacular light, especially for advertising	1880s–now
households	the usage of one electric appliances necessitated the availability of electricity, which allowed in turn to install many more different electric appliances which changed behaviour and led to a stronger dependence on electricity	1910s–now
households	the sales of devices and the general connectivity of households led to a great potential market of new electrical devices so that a generally innovative atmosphere was created in which inventions and sales mutually reinforced each other	1910s–now
households	the behaviour change resulting from the adoption of certain technology often resulted in a change of standards and societal norms; these norms changed behaviour of individuals eventually further so that adoption of more or different devices was triggered	1910s–now
households	behaviour changes could not seldom result in savings of money or time that led to new investments for product because time or money was there to afford them, eventually leading to more behaviour change	1910s–now
households	the savings resulting from behaviour changes, especially concerning time, trigger further behaviour changes, either for a different device or as a reinforcement of the originating behaviour	1910s–now
countryside	the availability of electricity in agriculture led to adoption of more electricity consuming appliances which often led to a higher efficiency and thus conserved the availability of electricity	1930s–now
countryside	use of electric technology in one farm, and the resulting benefits in efficiency led to adoption of electric technology in other farms too, because of the difficulty to remain competitive otherwise	1930s–now

3.4 Relying on the Magic: Electricity after the Infrastructurization

With the increasing integration and standardization of grids, frequencies, power capacities, or interfaces, the electric power network slowly became an infrastructure. The large steel frames that held cables in the 1930s looked very similar to those used in modern times, used frequency and voltage was regionally agreed upon, and everything but the countryside was connected to the electric grid (Nye, 1990). For the latter, this was only a matter of finances within the largely privately-financed electrification. Other countries followed similar pathways, maybe earlier, maybe later, maybe with more or less steering, but generally, electricity became an infrastructure by this time. Everything that came afterwards just increased the entrenchment of the infrastructure and the reached agreements, but the foundations were stable.

However, many of those identified dynamics still continued after the initial phase, and some of those are still the main characteristics for further entrenchment of the electricity system. On the one hand, there are the supply and generation of electric power, including the management of power plants, as well as innovation in the energy sector and network technology. All these innovations are responsible for the conservation of the electric power system, which include, for example, supply stability, risk minimization, and—since the first oil crisis in the 1970s—the diversification of the energy portfolio with alternative energy supplies. On the other hand, there is the consumption side of the electric power network, where novel appliances create ever more dependence on the power system, and where novel appliances create quasi-standards or implicit societal norms.

3.4.1 Conservation of the Electric Power System

Although power plants are nowadays not increasing in output power and size anymore, because power losses over long-distance transmission equalled out efficiency gains upon increasing plant size, there is still focus on network integration and load management. Nonetheless, power networks are being connected and controlled more than ever before, to cope with the increasing share of renewable energies whose output largely depends on the local weather conditions. This does not only imply regional integration, but also—especially within Europe, where legislation on power market liberalization is in place—the integration of different countries and remote regions, for example, of huge hydropower potentials in Norway or abundant wind power potentials in the North Sea with the metropolitan areas in Central Europe. These connections, that are often constructed with high-voltage direct current technology, do not only reduce risks of outages and increase system resilience, but they also help cutting costs and creating a more stable and diverse market.

Besides these developments on the electric power market, other developments in the energy sector took place, as well. Nuclear fission, natural and later liquefied natural gas (LNG) became part of the global energy sector. For these, novel artifacts—and later: infrastructures—were built or came into place. But their generativity is far below electricity because of the smaller range of exploitable related phenomena.

3.4.2 Continuing Increase of Functionality

The invention of new devices continued ever since the introduction of electricity into households and industries. On the one hand, technology became more mature or more sophisticated, but more importantly, whole new fields of technology emerged from the science and discoveries around electricity. Especially noteworthy is here the semiconductor technology, which allows all kinds of digital devices and technologies, such as the computers, cell and smart phones, or the internet. Furthermore important are the developments made in technologies using electromagnetic waves—which encompass not only radars or the radio, but also satellite or antenna-based television, wireless communication, and by now even wireless, pointed transmission of electricity—, and battery technology—allowing among others a wide range of mobile devices, that especially gain importance with semiconductor technology.
Huge achievements and novel developments of electric technology were, among many others, colour television, satellites, computers, medical equipment and tools, autonomous robots and automated systems. Based on all the achievements and new developments that came into place relying upon or related to electric power, it is unthinkable to live without it in modern times. The dependence that the usage of electricity in production or application of basically any good created for society is massive. Novel devices cannot revert this process of dependence on electricity, they rather increase it; however, the improvements of battery technology or mobile renewable energy systems allow a certain kind of independence from network access, allowing an increased resilience and independence from outer circumstances. Thus, apart from specialized applications, such as satellites, in the future no significant changes of this strong dependence upon the electric power network may be expected. Generally speaking, there are only a few technologies that are neither using electric power in their production nor during their application; one of these few exceptions are traditional musical instruments such as violins or guitars.
It still remains open, whether this process of increasing generativity can be generalized to serve other technologies. It seems, however, that for rather complex, novel, or groundbreaking technologies, as well as for new phenomena or novel concepts, the odds are high that generativity of these is equally high as for electricity. For example, written language, the wheel, or semiconductor technology most likely have such large generativity: they were continuously adopted and used in novel applications and processes, and are therefore irreversibly entrenched into the society, as well.

3.4.3 Novel Societal Standards

Any new device, any new appliance, technology or concept has the potential to become a societal standard or quasi-standard. I am too young, to judge upon the societal effects of anything I take for granted, such as colour television, radio, telephones, automobiles, high-speed trains, laundry machines, electric ovens, microwaves, and many more. But even in my rather short life, there are various changes and newly established technology-based quasi-standards that have not been there before. In a way, every single technology has the chance to become a standard or norm after initial adoption; especially for that those have high increasing returns of massive or rapid adoption (e.g. communication technology), the establishment of standards, and the consequent avoidance of inefficiencies, is an important factor for diffusion. Recently, these novel technologies include cell phones, computers and the internet, email addresses, social networks, mobile internet and smart phones, instant messaging, and many more. Any non-compliance with the implicit standards that have been adopted within the peer group may cause social isolation or disregard. In a way, the notions of being backward or inferior, which were already apparent with the usage or non-usage of electric lighting at the end of the 19th century, continue in new realms, but now based on other technologies.

4

Scaffolding Future Research: What Can Be Learned

All you really need to know for the moment is that the universe is a lot more complicated than you might think, even if you start from a position of thinking it's pretty damn complicated in the first place. — Douglas Adams (1992, Ch.17) in *Mostly Harmless*

In a way, everything mentioned in the theory is probably obvious, and in a way, everything from the case-study can be read elsewhere. The contribution here lies in the mental scaffold that the theory imposes when looking at the case-study. Or in more explicit words, this contribution tries to make the obvious visible and accountable by addressing currently underrepresented issues in transition and technology studies.

In the previous chapters, the underlying theory and framework were introduced and was discussed on the case-study of the electrification in detail; this chapter follows with a discussion of what use this thesis is. Therefore, at first the outcomes and insights gotten from analyzing the case-study will be discussed by looking into whether the electrification is a typical transition. Afterwards a discussion follows on the underlying theoretical ideas and finally the insights gained for the current understanding of electric power systems and the challenges it is facing.

4.1 The Electrification as a Phenomenon, Technology, and Successful Transition

The story of electrification seems to be the typical story of transitions: it replaced existing technologies. At first, learning experiences form a rudimentary niche which is isolated and has only very special applications. These applications are diverse and have multiple requirements to be met by the involved technologies; two of the three functions fulfill genuinely new applications and therefore do not fear any competition, but also do not have a large initial market. The third function, in contrast, has a large existing market, which however is harder to take over, and therefore the substitute technology powered by electricity remains a niche technology for long. Through the large functional diversity, electric technology has multiple independent developments paths that are self-standing in crises, but can profit from each other's achievements. In a way, positive impacts and developments are shared by spillover effects, while negative ones largely remain isolated within one sector.

When electric power started up, its rise was highly supported by the right business models that facilitated spread, as with the related plans and outsourced management effort, it was more convenient and affordable than other technologies. Besides this, it had not only a few initial applications and therefore functionalities, but also a few further applications that were yet undiscovered or at least unconsidered: motors and therefore mobility and industrial appliances, radiowaves, heating, and many more. Each of these functionalities became, upon introduction to larger markets, a new affordance of the electric power system in general, and in turn entrenched it further. Especially the generativity with respect to industrial and household appliances created a strong reinforcement of increasing functionality and conservation. The different introduced technologies that relied on electric power entrenched not only the usage of electricity in general, but also the concrete electric power network they relied upon. Economic forces of scale and load, as well as appropriate improvements of technology, allowed networks to grow, to standardize outputs and to form an integrated market.

On the other hand, the electrification seems to be an untypical transition. Most over all this is the case because it was not a technology or application that became entrenched and part of the society, but rather the phenomenon of electric power which is in a way completely different than any of its applications[24]. This means that the capacities of electricity are technology-independent, and can have their application basically anywhere, maybe just like any other phenomenon. Since any phenomenon is inherently generative, simply because of the structure of technology as recursive combinations of technologies and phenomena (see again Arthur, 2009), it may assumed that the entrenchment of such a phenomenon is very much different than the entrenchment of a basic technology. And actually, when treating electricity not as a technology, it becomes suddenly much clearer, why it was involved in a large variety of technologies, why it could set up many different functions before it even became applicable on the market. Treating electricity as a phenomenon, and electric technology as the surrounding domain, also allows to explain, why it became more generative over time, and why it could survive many subsequent versions and systems without losing many of the applications.

The answer to all this is, that phenomena are inherently generative, they can be applied in numerous different contexts, and can be mixed with other technologies. Over time, with the growth of professional electrical engineering, simply more of this generativity, more phenomena around electricity, were exploited and discovered, while subsequently the almost universal availability of potential applications for electric power made it economically desirable to increase network sizes; the results of this process are known. And since evolution—no matter whether it is biological or technical—never stops, it can be expected that many more inventions within electric technology are made, and humanity will continue being dependent upon it.

From both ideas combined and in light of the case-study, some universal ideas on successful transitions may be derived. Any transition starts with a window of op-

[24]Strictly speaking, it is not a single phenomenon called electric power, or electricity, but rather about all the different effects and mechanisms that are related to electricity, which are phenomena all by theirselves. In this way electricity would not be a simple phenomenon but rather a group of phenomena.

portunity for (i) a replacement for an existing technology, (ii) a new or improved version (i.e. with a novel function or characteristic) of an existing application, (iii) a new application, or (iv) a genuinely new concept or phenomenon, such as electricity. While (ii) can lead to comparatively quick success of a partial market, (iii) and especially (iv) may provide a larger growth scenario but also involve more uncertainty. On the other hand, (i) will have strong difficulties to prove its value on the market. Anyhow, these opportunities need to be exploited by technologies. At best, the same technology (or phenomenon) has a large diversity of potential or existing applications, and maybe it can even create novel functionalities by itself. Concerning technologies, this creativeness might be possible for more general parts of the system, such as subassemblies which may be used in a multitude of different final applications. By creating a wide diversity of functions, the technology becomes robust in its existence: any crisis or problem during the application will probably stay within the respective niche formed by a specific function; it will be simply a bad match. On the other hand, advancements from one application will positively impact the other technologies as well via spill-over effects and technological learning.
For becoming entrenched, as in becoming a stable regime or even part of the landscape, the technology needs to become a strong scaffold for the system. In this process, the created functionalities need to grow in usage and maturity, so that diverse dependencies for scaffolding interactions develop from the diverse opportunities; here it is not significant how strong the physical dependence is, but rather what would change if the technology would not exist anymore—the measure of entrenchment. This can be nicely illustrated with the examples from the electrification: for example, fire and burglar alarms were only minor consumers of electricity, but still contributed greatly to overall safety and could cut costs for personnel or insurances drastically. While the applications become mature, it is not unlikely—especially for a phenomenon, such as electricity—that further novel applications or replacements come into place.

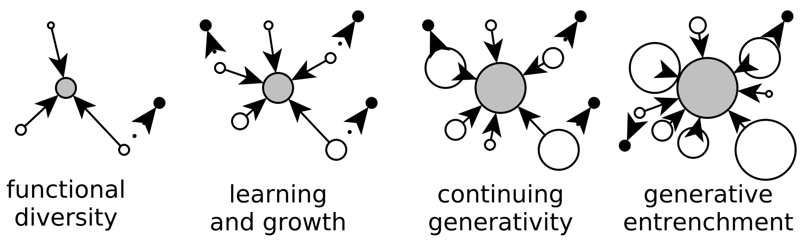

Figure 4.1: The abstracted order of processes during the generative entrenchment of the electricity.

Once a system grew to a certain extent it can be seen as entrenched; in the case of electricity, the electric power network, including all the physical necessities to generally use the advantageous technologies consuming electric power, became an infrastructure, and therefore an absolutely mandatory part of human life and interaction. For conventional and less creative technologies this will most likely not happen. Nonetheless, diversity is the key to remaining stable for any technology, since not only broad and deep dependencies of the technology, but also resilience towards potential competition in single markets is created.

4.2 Entrenchment Revised: Methods and Meanings

All of the three concepts this work builds up on have proved valuable and important, and only in combination allow the presented outcomes. The general frame of observation was contributed by Geels's (2002) multi-level perspective, which is fundamental to understand the overall sociotechnical systems in a holistic manner as being divided into regimes, niches and landscapes, jointly combined by internal and external interactions, coexistence and coevolution. Arthur's (2009) work on technological evolution is especially valuable when introducing entrenchment into a technological context. His ideas also prove very helpful for analyzing technology within the realm of evolution as *combinatiorial evolution*. Lastly, Wimsatt and Griesemer's (2007) work forms the overarching idea for analysis: these define the theoretical setting, the interactions between technologies (scaffolding) and also the resulting systemic states (entrenchment) and their functionality.

Although the outcomes of this study seem self-explanatory, within context, the application of the created theory brings many insights that would probably be invisible otherwise. In a way, it brought structure into the multiple pathways that the evolution of electric technology took as a consequence of its inherent generativity. Probably, it is exactly this generative context that makes the theory worthwhile applying. When, on the other hand, the technology in question is rather simple and clearly attributable to one single sociotechnical regime, or when the technology does not serve any socially significant scaffold, then the application of this extension of the MLP might not be valuable at all.

Apart from broadening the context and making it explicit, this concept also makes the context specific. But again, this is only valuable for the evaluation of transitions, if the context is of great importance and a large variety of different solutions, applications or boundary conditions is encountered; maybe it can be said, that this evaluation is appropriate, if we're dealing with *complex transitions*, as opposed to common transitions involving only one sociotechnical regime, or one less generative technology.

By focusing on developmental functions with the notion of scaffolding, the importance of society, its basic structure, and its activities are reinforced strongly. What would happen, if a specific element was not there anymore? This central question can guide identification of critical factors and influences in transitions, and can contribute to a more holistic analysis of technologies, especially when embedded into more complex sociotechnical systems or involved into a large variety of realms. Scaffolding as described here, can not only foster and facilitate the achievement of novel developmental functions but also is scaffolding crucial for the overall functioning of society. Existing sociotechnical regimes scaffold other sociotechnical regimes via their respective facilitation of development. This reinforces the current function of the regimes, supports standardization and ultimately locks-in the scaffolding sys-

tems. These obvious but still powerful ideas integrate perfectly into the multi-level perspective and can help understanding the dynamics of transitions or the lack of transitions further.
On the other hand, besides all the qualities and advantages, there are some drawbacks about the presented concept. Quantitative analysis is as impossible as clear attributions of regimes and functions, or a high accuracy. It is rather based on narratives, which is at maximum as precise as the sources, and necessitates high receptivity from the researcher for acquiring all the data and bringing them into a meaningful connection and context. Making the obvious visible in this case comes of course also with a lot of further considerations and an increase in complexity that has to be justified with the inherent complexity of the context that has to be accounted for appropriately.
In a way, there are no really good alternatives for the presented ideas. For not overly complex systemic dependencies of technology, it might not be worth the effort to include the scaffolding environment and entrenchment perspectives; in this case, it would be more fruitful to simply apply a traditional multi-level perspective or other methods from transition studies. Also, it remains open, whether the presented concepts are helpful for not only gaining a backward-looking understanding but also for forward-looking frameworks from transition management (e.g. backcasting) with respect to planning or understanding of potential transitions. Otherwise, it might also be possible and fruitful to adapt the presented ideas into other frameworks dealing with sociotechnical systems and developments, as the novel context might bring certain extra benefit to the understanding.

4.3 What's Next? The Future of Electricity

Not only can the concept introduced contribute to future research in transition and innovation studies, but also may the case-study and the insights gained into the electricity system contribute to future energy transitions research. Today, the world is facing a vast amount of environmental problems, especially related to the green house gas emissions that come from a large consumption of electric power originating in combustion of fossil fuels. This thesis showed, how the electric system that is taken for a granted infrastructure today, was formed and how it became such a deeply entrenched necessity for society: in the beginning, a variety of different applications made the electric system gain experience, grow, and, over time, become what it is today. Its inherent generativity with respect to potential applications allowed for ever new or improved applications, and ever more production and control over the processes. These new applications changed society so that new technologies became used, their usage became widely spread, and this finally led to new standards and norms being established as a result. They made electricity deeply entrenched as basis to our daily lives, our norms and customs, while at the same time providing opportunity for even more consumption of electricity. It became a highly significant scaffold for today's society, and although not every application of electric power might be crucial for a proper functioning of society, humanity and society as a somehow working system are completely dependent. This systemic dependence caused governments and utilities invest even more into infrastructure, to reduce the risk of outages even further, and at the same time increasing their control of the system even more.

All these dynamics are ongoing until today as described in section 3.4, so that it is unimaginable to simply cut out electricity, it will instead get even bigger and gain more importance. Trends towards energy efficiency within a large variety of appliances are similarly gaining importance; however, this does simply reduce the amount of electricity needed, but its scaffolding purpose remains unchanged. In this way—despite the reduction in greenhouse gas emissions, of course—it may be irrelevant to talk about a reduction of electricity consumption driven by efficiency improvements when the systemic necessity of electricity remains stable. Certainly any improvement of efficiency will cause the input to the electric power system and thus also the emissions to decline, but actually the entrenchment per unit of output would increase within the same process, making the electric power system even more sensitive for change or disruption. Of course, an increase in sensitivity is not a reasonable argument to limit efficiency improvements, as any efficiency improvement reduces input requirements, and thus limits the problems of the electric power sector. But in a way, this does not solve the problems, it only reduces them.

Coming back to the lessons from history, the history of electric power also showed centralization of production systems, and decentralization, or maybe spread and diffusion, of consumption systems: both of these systems are deeply entrenched in their own way, too. However, due to the tripartite structure of electric power systems, any change in either of these two will not affect the other directly, but instead the transmission network has to cope with the change. Since not the generation but only the application of electricity is deeply entrenched within the whole society, for the end user any change in the production network is not relevant as long as the qualities, such as a stable, reliable, secure, fairly cheap, and almost universal consumption of electricity is guaranteed. In this way, it is worth looking at battery technology and distributed renewable energy generation. Despite that the necessary construction materials for batteries or renewable energy plants are limited—just as fossil fuels are—, they may be able to cut greenhouse gas emissions. Especially renewable energies are a promising replacement for fossil fuel-based electric power supply, although their intermittent nature has to be coped with. As elaborated earlier, this could be done by increasing grid size and constructing more energy storage facilities. One of these storage facilities may also be batteries, which are yet too small to cope with long-term seasonal fluctuations of, for example, solar power availability. However, batteries as decentralized components of the electric power system are a promising technology: on the one hand, when users are not requiring electric power continuously because their devices have their own buffer, any change in electricity supply is not as relevant as it was when a constant power supply was needed. On the other hand, the vast amount of batteries in a domestic homes might also be used as a storage opportunity for the electric power network. However, for both opportunities, the necessary technology allowing intermittent power supply or reversing power flows in domestic homes, are often still nonexistent[25]. Would this be the case, then the

[25]The technology described here is often called a *smart meter*, an electricity meter that is able to communicate with the electricity-consuming devices and steer them, to create flexibility about the time and amount of used power. An electricity system based on smart meters is often called *smart*

very strict requirements towards the electric power system could either loosen up by rigidity on the application side, or be easier to match for the supply side by co-operation and communication mechanisms with and on the demand side.
Of course, saying that only the application of electricity is entrenched, is a little bit too simplified. In fact, also the current production system is entrenched, just not as deeply and not in the whole of society: instead, it is entrenched as an highly profitable and fairly stable source of income for the large corporations managing electric power plants, but also for its employees and the related businesses within the supply chain. This of course creates barriers to change, and even economic incentives to fight against any attempts to break this structure, for example by a decentralization of actors in the electric power market. Furthermore, central power plants are often entrenched into the surrounding industrial areas for cooperative actions, as well as into the surrounding communities as a bigger employer and sponsor, and for district heating systems. So actually, neither from a systemic side, nor from a societal side, is there any factor that would hinder any change in electricity generation systems. These barriers instead come from economic power of the involved companies, and maybe in the same turn from economic lock-ins.
From a technological side, there are no missing scaffolds, no barriers to overcome. Since the oil crisis, renewable energy systems have been under constant development and improvement. Their importance grew bigger in the last decades: at first with the support through government interventions, but recently renewable energy systems became competitive even on larger scales. But there are still two important restrictions that do not equal the scaffolding surrounding of fossil fuel-based power plants. At first, renewable energy systems have a fairly low energy density with respect to the used area, so that more area is needed. However, since they are also more feasible on smaller scales, this would open up for a re-decentralization of electric power that theoretically could also decrease transmission losses and risk of outages. Secondly, there is a strong dependence for energy storage due to the intermittency of renewable energies. Potential solutions to this, such as hydropower storages or more flexible or rigid electricity consumption, have been discussed above.
Besides all these speculations on the future of electricity, there are only a few certain things: the reinforcement called generative entrenchment will continue, and with it the dependence of society upon electricity. Also, there will be ever more new devices, and ever more new societal norms standards emerging from these, so that society in its shape and function will co-evolve further together with electric power systems. There is simply no option to drop out of this increased dependence. And although electric power will still become more entrenched and thus conserved, the future might bear some opportunities to disentangle supply and demand side more, and hence to loosen the dependence of an until now crucial quality of electric power systems: the temporal synchronicity of input and output, which of course cannot be overcome physically, but at least from a management point of view. Those means as discussed above, of increased rigidity or flexibility on the supply side, seem to be the most promising options to achieve a disentrenchment of societal dependence on electric power.

grid, and also involves, for example, flexible tariffs for electricity usage and buffering of electricity in the batteries of electric cars.

5

Conclusion

History is written by the victors.
— unknown origin, attributed to Winston Churchill

This thesis involved a lot of different ideas and concepts that framed dozens of pages of elaborations and descriptions of some historical contexts, often from more than a hundred years ago, that was called case-study. There was quite some effort needed to compile the data, integrating it into a meaningful storyline and theoretical context, and ultimately drawing results from it. Some of those results are specific to the case discussed, some can be generalized to transition studies or to electric power systems in general, some may have even more opportunity to be generalized further. On the one hand, this thesis is not much more than a bunch of words and sentences arranged to summarize the efforts of five hard months of research and thought processes; nonetheless, this thesis is eye-opening towards the complexity of transition studies and the multitude of issues involved in monitoring and observing technological change, innovation, and novelties in complex societal surroundings.

The electrification was a complex process involving a large variety of different actors with different motives, different incentives, and different influences. Although the real electrification only began with the spread of electric light, the basics and foundations for these achievements, the whole supporting artifacts and infrastructures were set up and built in the century before. Besides technical achievements, also novel supply schemes, that separated application from generation of electricity, were important factors for the sudden success. Following this, the general attraction towards electric light, as well as its technical and economic advantages over petroleum or gas light, started a still ongoing, almost magical relationship between people and electricity. Besides the fact that it could attract people to cities, fairs, business areas, shopping streets, or stores; on the flipside of the medal, anything that did not have electric light was soon considered backwards, and social Darwinist ideologies emerged around electricity. Later, with the rise of electric streetcars, electricity shaped the structure of cities and thus society, and the urban sphere became reorganized and restructured as a consequence of cheap and easy opportunities for personal mobility. After a while, also industries became electrified; just as the availability of electric light and thus electric power also triggered the invention of new appliances, the installation of electricity in industries electrified whole sectors and production lines, which later also led to huge efficiency improvements once the advantages of electric engines were fully used in production systems. Following the electrification of the industries, the electrification of households also became affordable, mainly because of low opportunity costs and economic incentives for the utility.

In turn, with the wide spread of electricity in households, also more and more inventions were made, and soon households in the United States consumed more than the industries. With the general electrification of farms and rural communities after WWII, the electrification can be seen as finished. It became an infrastructure as known today: a large-scale, standardized, integrated, and properly managed system to provide everyone with electric power.

Within this story, many elements and features can be found, that can be seen in the light of the presented frameworks: reinforcement of conservation, functionality and entrenchment, infrastructurization and standardization, the process of electricity becoming part of different realms of society, how different technologies showed up, and how diverse electric power systems were used. It was shown which general trends and overarching dynamics shaped and still shape society's relationship towards electricity, which actually may help solving modern issues with electric power systems.

The complexity of the analysis, as well as this diversity, are the central points to this thesis: an application of the presented framework of scaffolding and generative entrenchment is only meaningful, if the analyzed technology is generative enough. This means, that the technology can be either utilized in many different applications, and is therefore a sub-technology or simply a physical phenomenon that is exploited by technology. In these cases, the variety of applications can be numerous and maybe even endless, and their range of usage is not bound to specific sectors or ideas but rather universal and only limited by human creativity. Indeed, any less concrete but rather abstract technology may not solely be analyzed with frameworks from traditional transition studies, but needs some more novel approaches: approaches, like the presented, that fit the technology into a preceding story, into subsequent happenings, and into the complex context of human society. Only then, the full extent of this specific technological change or transition may be understood appropriately, although even here complete understanding seems still very far.

However, it needs to be acknowledged, that the framework used is rather undefined and less concrete. Instead, it opens up for a lot of interpretation, and it actually demands a narrative rather than quantitative data, as this does simply cut out the necessary complexity. Nonetheless this narrative is based upon sources, and sources are always incomplete or insufficient. I am really thankful to the numerous scholars who have written about the electrification and the history of electric technology, but one also has to see, that their view is as much biased as ours. In fact, only the stories of others were retold, put them in a different light, and hope that our understanding of their representation of decade-old events is roughly adequate to the reality back then; but this is a problem which backward-looking science generally has to cope with. Maybe with different information, or different context of the information, the outcomes of this thesis might have been very different, and there always need to be aware of this. Any generalization, any idea, any notion that can be gotten from the stories, from their retelling, is just the end of numerous filters and objectives that framed reality. Therefore, already any account of the reality changes its perception, it reduces complexity and simplifies issues that are sought to be treated in its wickedness.

Concerning possible future research on this topic, still many more case-studies on

different more or less complex technologies and phenomena are needed. Additionally, more cultural and habitual aspects should be included into the framework, and more focus might be laid upon a wider diversity of narratives. In this thesis, only a very small amount of different stories or even scholars has been used, to make a point for a whole country. In fact, maybe the situation in neighbouring communities of those who got attention in our secondary sources, the situation might have been completely different. More primary sources might need to be involved, and if appropriate and feasible even interviews with the involved population.
The analysis also showed that the context is important, that every transition is different, every single adoption of technology is shaped by slightly different circumstances, motives, or ideas. This can be only coped with by getting a wider range of sources. If done appropriately, the used framework may also be applied to numerous other regimes and sectors of societal relevance. Besides energy this can be also food, communication devices, education, media, or even retailing. Potential examples may be just as endless as the generativity of electricity.

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